High-energy vacuum birefringence in an intense laser field

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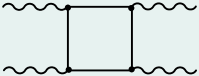
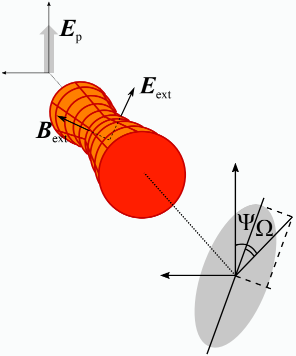
Vacuum polarization



- Vacuum birefringence:
  Different refractive indices for two different polarizations.
- Vacuum dichroism (via $e^- e^+$ pair production):
  Different absorption for two different polarizations.



Small vacuum polarization limit (linearly polarized probe photons)

- Birefringence: Ω (ratio of the ellipse axes).
- Dichroism: Ψ (major axis rotation).

Introduction: Vacuum birefringence and dichroism

Vacuum magnetic birefringence

$$\Omega \sim \omega_{\rm p} B^2 L \sim 10^{-11}.$$

F. Della Valle et al., Phys. Rev. D 90, 092003 (2014).

How to improve the vacuum birefringence effect

- Increasing the field strength $\rightarrow$ high-intensity optical lasers (A^μ, k^μ, $k^0 = \omega_{\rm L}$, $k_\mu k^\mu = 0$, $\omega_{\rm L} \sim 1$ eV).
- Increasing the probe photon energy $\rightarrow$ gamma photons (q^μ, $q^0 = \omega_{\rm p}$, $q_\mu q^\mu = 0$).

B. King & N. Elkina, Phys. Rev. A 94, 062102 (2016); A. Ilderton & M. Marklund, J. Plasma Phys. 82, 655820201 (2016); Y. Nakamiya et al., arXiv:1512.00636; V. Dinu et al., Phys. Rev. D 89, 125003 (2014).

Parameters ($\hbar = c = 1$)

Classical intensity parameter:

$$\xi = \frac{|e|E}{m\omega_{\rm L}}.$$

$\xi \sim 100$ for $I \sim 10^{23}$ W/cm^2.

Quantum nonlinearity parameter:

$$\chi = \frac{kq}{m^2}\xi \overset{\text{head-on}}{=} \frac{2\omega_{\rm p}\omega_{\rm L}}{m^2}\xi.$$

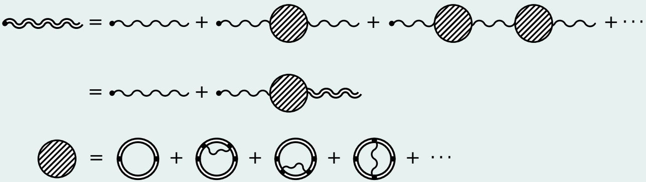
$\chi \sim 1 \rightarrow$ pair production is sizable. ($\omega_{\rm p} \sim 1$ GeV, $I \sim 10^{23}$ W/cm^2)

Outline of the talk

- Vacuum birefringence and dichroism in a linearly polarized strong plane-wave field.
    - Radiative corrections to probe photon propagation, Dyson equation.
    - Locally constant crossed field approximation.
- Feasibility of a high-energy vacuum birefringence experiment.
    - Setup, gamma photon generation and detection.
    - General polarization of the probe photon beam: density matrix, Stokes parameters.
    - Statistical analysis and estimations.

Exact photon line

Dyson equation



$$-\partial^\sigma \partial_\sigma \Phi^\mu(x) = \int \mathrm{d}^4 y P^{\mu\nu}(x,y)\Phi_\nu(y).$$

Laser pulse

$$A^\mu(kx) = a^\mu \psi(kx).$$

$$a^2 < 0,\ ka = 0; \quad |\psi(kx)|,\ |\psi'(kx)| \lesssim 1; \quad f^{\mu\nu} = k^\mu a^\nu - k^\nu a^\mu;$$

$$\{L_1^\mu, L_2^\mu\}: \quad L_1^\mu = \frac{f^{\mu\nu} q_\nu}{kq\sqrt{-a^2}}, \quad qL_i = kL_i = 0, \quad L_i^\mu L_{j\mu} = -\delta_{ij}.$$

Dyson equation ($\xi \gg 1$, $\chi \lesssim 1$)

$$-\partial^\sigma \partial_\sigma \Phi^\mu(x) = P^{\mu\nu}(kx, \chi)\Phi_\nu(y),$$

$$P^{\mu\nu}(kx, \chi) = -\left[p_1(kx, \chi) L_1^\mu L_1^\nu + p_2(kx, \chi) L_2^\mu L_2^\nu\right],$$

$$p_1(kx, \chi) = \frac{\alpha m^2}{3\pi} \int_{-1}^{1} \mathrm{d}v (w-1) \frac{f'(u)}{u}, \quad p_2(kx, \chi) = \frac{\alpha m^2}{3\pi} \int_{-1}^{1} \mathrm{d}v (w+2) \frac{f'(u)}{u},$$

$$w = 4/(1-v^2), \quad u = [w/\chi|\psi'(kx)|]^{2/3}, \quad f(u) = \pi\left[\mathrm{Gi}(u) + i\,\mathrm{Ai}(u)\right].$$

Solution

$$\Phi^{(0)\mu}(x) = \epsilon^{(0)\mu} \mathrm{e}^{-iqx} = \sum_{i=1,2} b_i^{(0)} L_i^\mu \mathrm{e}^{-iqx} \;\to\; \Phi^\mu(x) = \sum_{i=1,2} b_i^{(0)} \mathrm{e}^{i\phi_i} \mathrm{e}^{-\lambda_i} L_i^\mu \mathrm{e}^{-iqx}.$$

$$\phi_i = -\frac{1}{2kq} \int_{-\infty}^{\infty} \mathrm{d}\phi\, \mathrm{Re}\left[p_i(\phi, \chi)\right], \quad \lambda_i = -\frac{1}{2kq} \int_{-\infty}^{\infty} \mathrm{d}\phi\, \mathrm{Im}\left[p_i(\phi, \chi)\right].$$

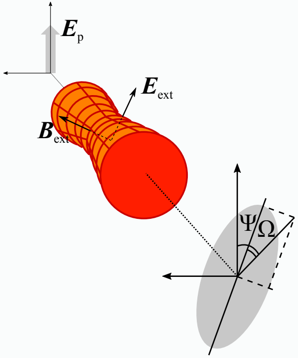
S. Meuren et al., Phys. Rev. D 91, 013009 (2015).

Vacuum birefringence and dichroism

Difference of the two components

$$\delta\phi = \phi_2 - \phi_1 = -\frac{1}{2kq}\int_{-\infty}^{\infty} \mathrm{d}\phi \, \mathrm{Re}\left[p_2(\phi,\chi) - p_1(\phi,\chi)\right],$$

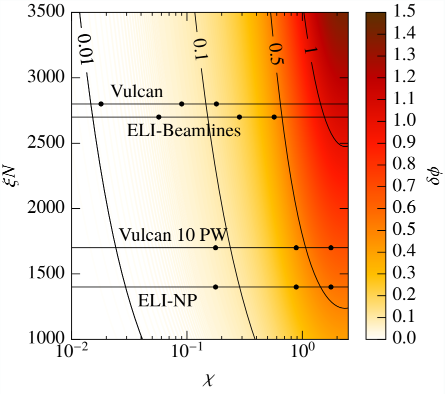
$$\delta\lambda = \lambda_2 - \lambda_1 = -\frac{1}{2kq}\int_{-\infty}^{\infty} \mathrm{d}\phi \, \mathrm{Im}\left[p_2(\phi,\chi) - p_1(\phi,\chi)\right].$$

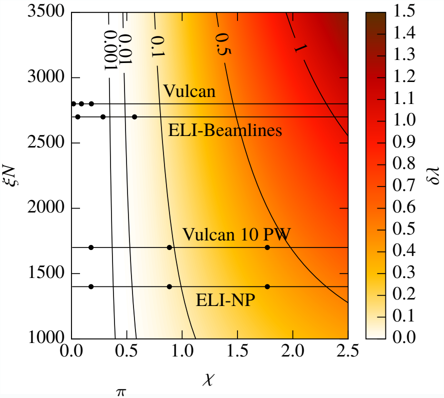


Small vacuum polarization limit (linearly polarized probe photons)

- Birefringence: $\Omega \propto \delta\phi$.
- Dichroism: $\Psi \propto \delta\lambda$.

Overview of the effects





Rectangular pulse envelope:

$$\psi'(kx) = \begin{cases} \sin(kx), \, kx \in [-N\pi, N\pi], \\ 0 \quad \text{otherwise.} \end{cases}$$

$$\delta\phi = \frac{\xi N}{m^2 \chi} \int_0^{\pi} \mathrm{d}\phi \, \mathrm{Re}\left[p_1(\phi,\chi) - p_2(\phi,\chi)\right],$$

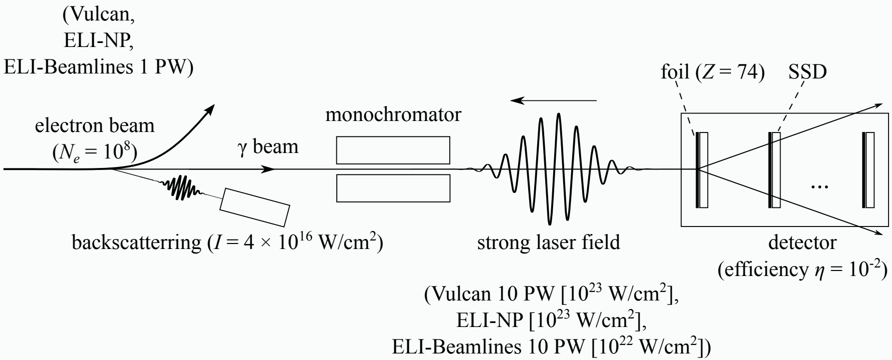
$$\delta\lambda = \frac{\xi N}{m^2 \chi} \int_0^{\pi} \mathrm{d}\phi \, \mathrm{Im}\left[p_1(\phi,\chi) - p_2(\phi,\chi)\right],$$

$$\psi'(\phi) = \sin(\phi).$$

Optimal regime

$\chi \sim 0.1$, $\delta\phi \sim 0.1$
($\omega_{\mathrm{p}} \sim 10^2$ MeV for 10 PW).

High-energy vacuum birefringence experiment



Gaussian pulse envelope: $\psi'(kx) = \mathrm{e}^{-(kx)^2/\Delta\phi^2} \sin(kx)$.

See also: B. King & N. Elkina, Phys. Rev. A 94, 062102 (2016); A. Ilderton & M. Marklund, J. Plasma Phys. 82, 655820201 (2016); Y. Nakamiya et al., arXiv:1512.00636.

Probe photon beam polarization

Calculation of an observable

$$W \propto |M|^2 = M_\mu M_\nu^* \epsilon^\mu \epsilon^{*\nu}.$$

Density matrix

$$\epsilon^\mu \epsilon^{*\nu} \to \rho^{\mu\nu} = \sum_a w_a \epsilon_a^\mu \epsilon_a^{*\nu} = \sum_{i,j=1,2} \rho_{ij} \Lambda_i^\mu \Lambda_j^\nu .$$

$$\{\Lambda_1^\mu, \Lambda_2^\mu\} : \quad q\Lambda_i = k\Lambda_i = 0, \quad \Lambda_i^\mu \Lambda_{j\mu} = -\delta_{ij}.$$

$$\begin{pmatrix} L_1^\mu \\ L_2^\mu \end{pmatrix} = R(\varphi_\mathrm{L}) \cdot \begin{pmatrix} \Lambda_1^\mu \\ \Lambda_2^\mu \end{pmatrix}, \quad R(\varphi_\mathrm{L}) = \begin{pmatrix} \cos\varphi_\mathrm{L} & \sin\varphi_\mathrm{L} \\ -\sin\varphi_\mathrm{L} & \cos\varphi_\mathrm{L} \end{pmatrix}.$$

Stokes parameters

$$\rho = \frac{1}{2}\left(S_0 \mathrm{I} + \boldsymbol{S} \cdot \boldsymbol{\sigma}\right),$$

$\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$ - the Pauli matrices,

$S = \{S_0, \boldsymbol{S}\}$ $[\boldsymbol{S} = (S_1, S_2, S_3)]$ - the Stokes vector.

Probe photon beam polarization

Connection between the Stokes parameters

$$\rho = T\rho^{(0)}T^{\dagger},$$

$$T = R^{-1}(\varphi_{\mathrm{L}}) \begin{pmatrix} \mathrm{e}^{i\phi_1-\lambda_1} & 0 \\ 0 & \mathrm{e}^{i\phi_2-\lambda_2} \end{pmatrix} R(\varphi_{\mathrm{L}}).$$

Pair production cross section

$$\mathrm{d}\sigma_{\mathrm{pp}} = \frac{\mathrm{d}\varphi}{2\pi}\left\{S_0\sigma^{(0)} + [S_1\sin(2\varphi) + S_3\cos(2\varphi)]\sigma^{(1)}\right\},$$

φ — azimuth angle for the created pair,

$\sigma^{(0)}$ — cross section for an unpolarized beam, $\sigma^{(1)} \sim 0.1\sigma^{(0)}$.

Note: the cross section $\mathrm{d}\sigma_{\mathrm{pp}}$ does not depend on S_2.

Laser polarization is rotated by $\varphi_{\mathrm{L}} = \pi/4$ with respect to the detector axes.

Linear polarization

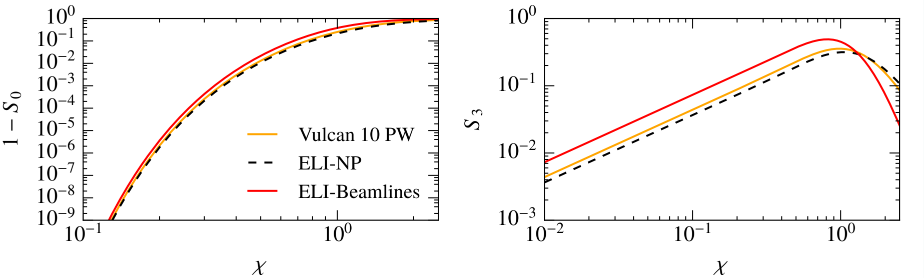
$S^{(0)} = \{1, 0, 0, 1\}$

$$
\begin{aligned}
S_0 &= \quad \mathrm{e}^{-(\lambda_1+\lambda_2)} \cosh \delta\lambda, \\
S_1 &= \quad \mathrm{e}^{-(\lambda_1+\lambda_2)} \sinh \delta\lambda, \\
S_2 &= -\mathrm{e}^{-(\lambda_1+\lambda_2)} \sin \delta\phi \approx -\delta\phi, \\
S_3 &= \quad \mathrm{e}^{-(\lambda_1+\lambda_2)} \cos \delta\phi \approx 1 - (\delta\phi)^2/2.
\end{aligned}
$$

Circular polarization

$S^{(0)} = \{1, 0, 1, 0\}$

$$
\begin{aligned}
S_0 &= \mathrm{e}^{-(\lambda_1+\lambda_2)} \cosh \delta\lambda, \\
S_1 &= \mathrm{e}^{-(\lambda_1+\lambda_2)} \sinh \delta\lambda, \\
S_2 &= \mathrm{e}^{-(\lambda_1+\lambda_2)} \cos \delta\phi \approx 1 - (\delta\phi)^2/2, \\
S_3 &= \mathrm{e}^{-(\lambda_1+\lambda_2)} \sin \delta\phi \approx \delta\phi.
\end{aligned}
$$

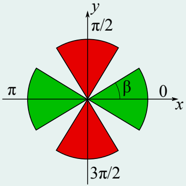


Detection and statistics

Observable

$$R_{\mathrm{B}} = \frac{(N_0 + N_\pi) - (N_{\pi/2} + N_{3\pi/2})}{N}.$$

$$\langle R_{\mathrm{B}} \rangle = \frac{\sin(2\beta)}{2\beta} \cdot \frac{\sigma^{(1)}}{\sigma^{(0)}} \cdot \frac{S_3}{S_0} \approx \frac{\sin(2\beta)}{2\beta} \cdot \frac{\sigma^{(1)}}{\sigma^{(0)}} \cdot \delta\phi.$$



Statistics

$N \gg 1$: $R_{\mathrm{B}} \in \mathcal{N}(\langle R_{\mathrm{B}} \rangle, 1/N)$.

Verification/rejection at $n\sigma$ confidence level:

$$N_\gamma^{\mathrm{B}} = \frac{\pi n^2}{\eta \beta \langle R_{\mathrm{B}} \rangle^2} \cdot \frac{\mathrm{e}^{\lambda_1 + \lambda_2}}{\cosh \delta\lambda}. \qquad (\beta_{\mathrm{opt}} \approx 33^\circ)$$

Duration of the experiment (3σ)

- CLF: 260 days. (10^{23} W/cm^2, 30 fs, 2 shots/hour [Vulcan])
- ELI-NP: 13 days. (10^{23} W/cm^2, 25 fs, 1 shot/minute)
- ELI-Beamlines: 4 days. (10^{22} W/cm^2, 150 fs, 1 shot/minute)

- High-energy vacuum polarization experiments in a strong laser field are promising for testing QED (and searching for physics beyond the Standard Model).
- In this regime it is important to take both vacuum birefringence and dichroism into account.
- For the high-energy vacuum birefringence experiment a significant improvement is obtained if employing circularly polarized probe photons.
- The experiment is feasible at the upcoming laser facilities (the expected duration of the experiment is a few days for the 3σ confidence level).

Thank you for your attention!