Quantum reflection off electromagnetic fields

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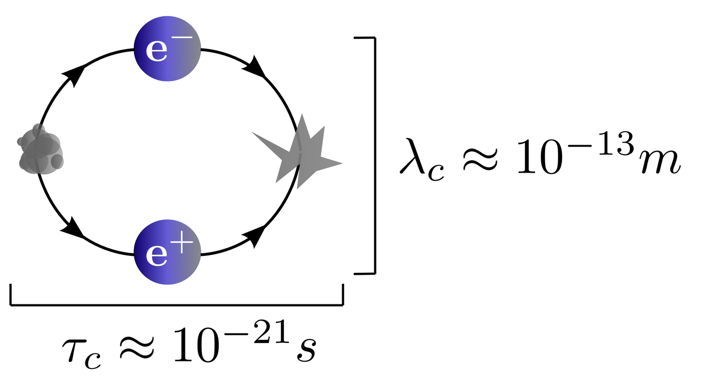
Introduction

The theory of quantum electrodynamics (QED) predicts that electromagnetic fields in vacuum exhibit nonlinear interactions once the field strength approaches $\mathcal{E}_{\rm cr} = m^2/e \approx 10^{18}\mathrm{V/m} \approx 10^9\mathrm{T}$ [1]. These interactions are facilitated by virtual electron-positron fluctuations which permeate the quantum vacuum.

Advances in the development of high-intensity lasers put the experimental verification of optical vacuum effects in reach for the first time. We investigate quantum reflection [2] as a possible signature of the quantum vacuum nonlinearities, and give estimates for an experimental set-up employing high-intensity lasers.



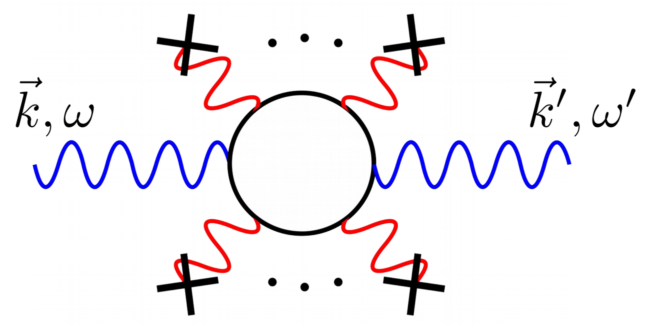
Photon propagation in inhomogeneous backgrounds

Effective theory for probe photons of arbitrary frequency propagating in an external electromagnetic background field $\mathcal{E}(x)$ yields the equations of motion:

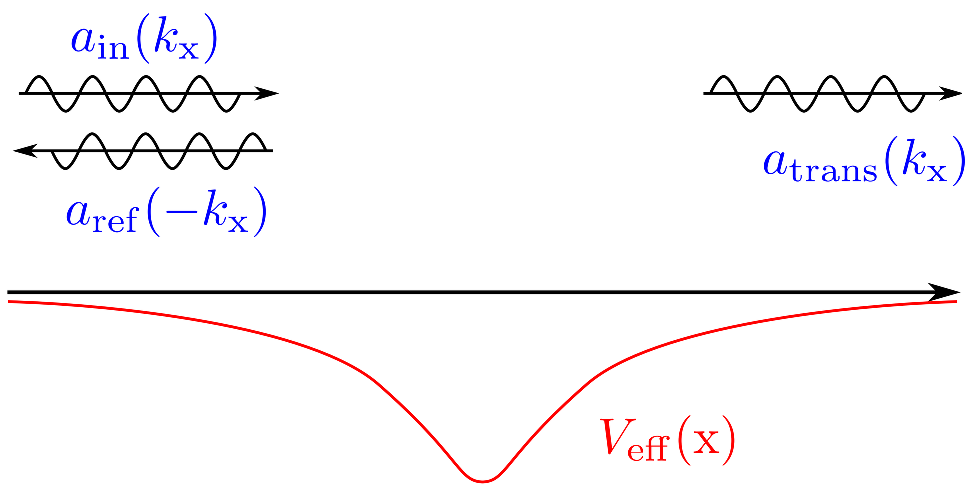
$$(k^2 g^{\mu\nu} - k^\mu k^\nu) a_\nu(k) = -\int \frac{d^4k'}{(2\pi)^4} \tilde{\Pi}^{\mu\nu}(k,-k'|\mathcal{E}) a_\nu(k')$$

Quantum Reflection:

The quantum vacuum, when subjected to a strong background field, acts as an effective (attractive) potential for traversing probe photons. Inhomogeneous backgrounds can transfer energy/momentum onto probe photons, which leads to "quantum reflection" (= above-the-barrier scattering) [3].



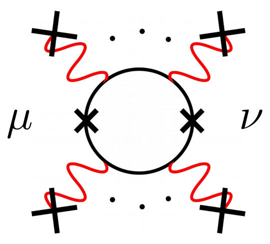
Diagrammatic depiction of quantum reflection



1D above-the-barrier scattering in an inhomogeneous effective potential.

Photon polarization tensor

(One-loop) Photon polarization tensor in an electromagnetic background field:

$\Pi^{\mu\nu}(x,y|\mathcal{E}) \quad = \quad \mu$  ν

- Analytical expressions are only available for constant [4] or plane-wave [5] backgrounds, but quantum reflection manifestly requires inhomogeneous fields.
- Start with analytical expression for constant background fields, and incorporate inhomogeneities by means of a locally-constant field approximation (LCFA):

$$\Pi^{\mu\nu}(k')\,\delta^{(4)}(k-k') \xrightarrow{\text{F.T.}} \Pi^{\mu\nu}(x-x') \xrightarrow{\mathcal{E}\to\mathcal{E}(x)} \Pi^{\mu\nu}(x,x') \xrightarrow{\text{F.T.}^{-1}} \Pi^{\mu\nu}(k,k')$$

- Restricted to scenarios which conserve the polarization p of probe photons in order to preserve gauge-invariance ("Ward-identity"):

$$\partial_\mu \Pi^{\mu\nu}(x,x') \stackrel{!}{=} \partial'_\nu \Pi^{\mu\nu}(x,x') \stackrel{!}{=} 0$$

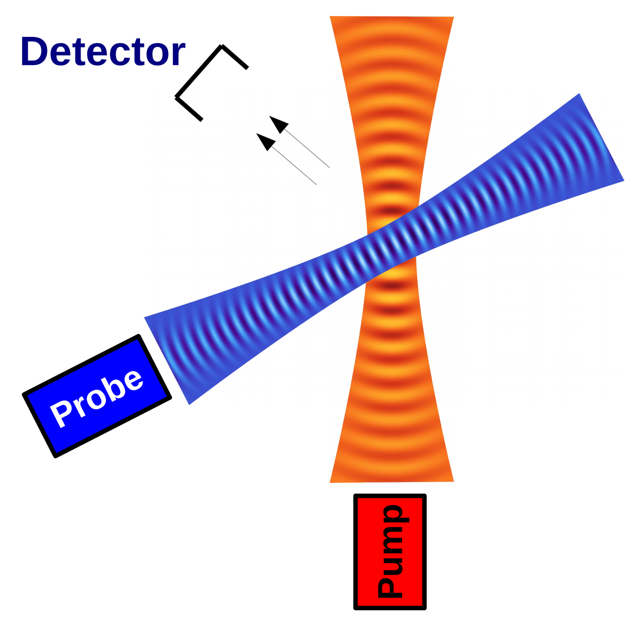
- For crossed background fields ($\vec{E} \perp \vec{B}$, $|\vec{E}| = |\vec{B}| = \mathcal{E}$), varying in time and along (up to) two spatial directions, we derived analytical expressions for the polarization tensor in the weak-field limit $\mathcal{E} \ll \mathcal{E}_{\rm cr}$ [6].

⟶ Utilize to model focused laser beams as background!

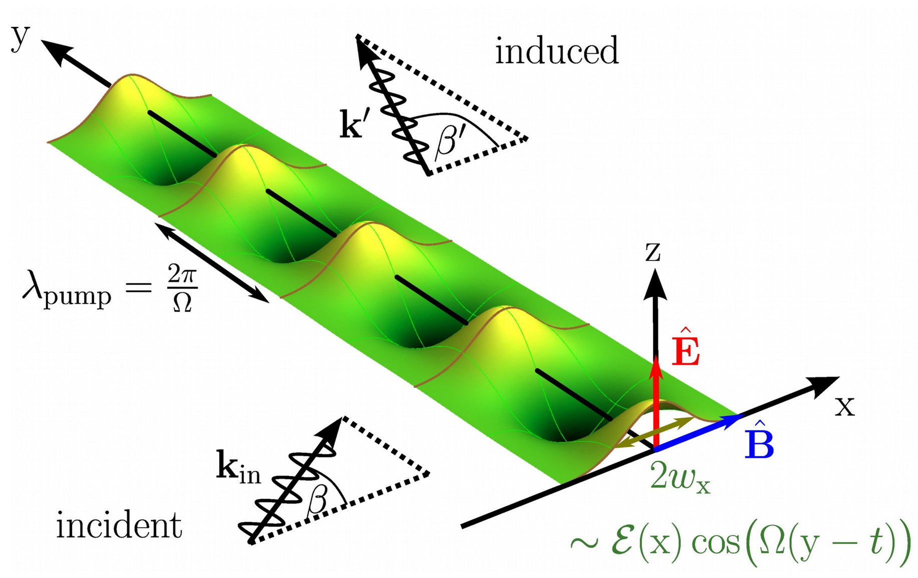
Towards possible experiments

Envisage a pump-probe type experiment employing high-intensity lasers, searching for quantum reflected photons in the free field region:

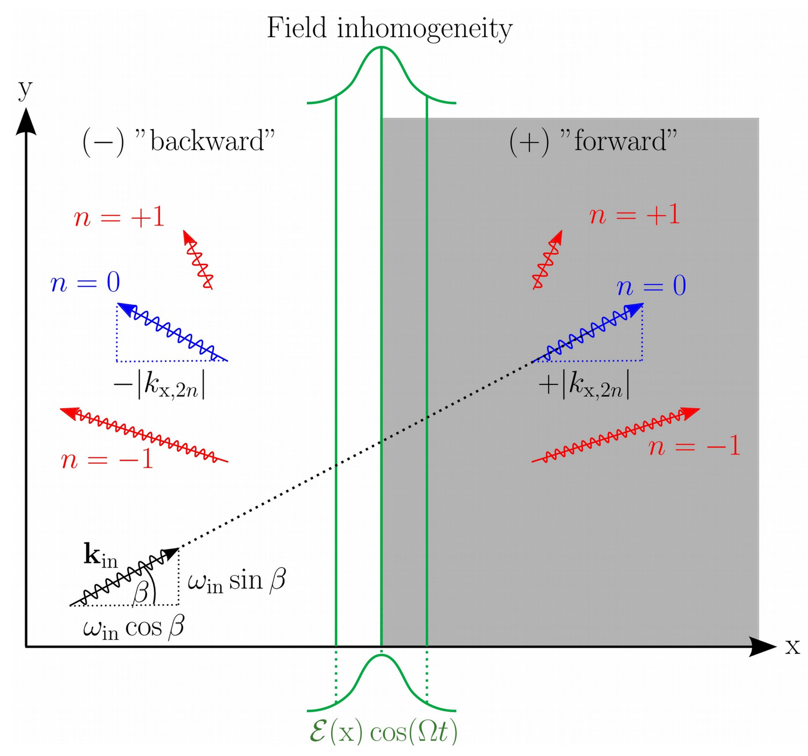
Experimental set-up



Theoretical model



Our theoretical model encompasses the basic features of quantum reflection off the focal spot of a propagating laser beam. The harmonic time dependence $\cos(\Omega(\mathrm{y}-\mathrm{t}))$ gives rise to both elastically ($n=0$) and inelastically ($n=\pm1$) scattered photons, with frequencies $\omega'_{2n} = \omega_{\rm in} - 2n\Omega$ (cf. the schematic on the right).



Scattering coefficients:

$$R^{(\pm)}_{p,2n} \propto \left| \frac{\alpha}{\pi} \frac{\omega_{\rm in}^2 (1-\sin\beta)^2}{k_{\rm x,2n}} \int \mathrm{d}x\, \mathrm{e}^{i(\omega_{\rm in}\cos\beta \mp |k_{\rm x,2n}|)\rm x} \left(\frac{e\mathcal{E}(\rm x)}{m^2}\right)^2 \right|^2 + \mathcal{O}\left(\left(\tfrac{e\mathcal{E}}{m^2}\right)^6\right)$$

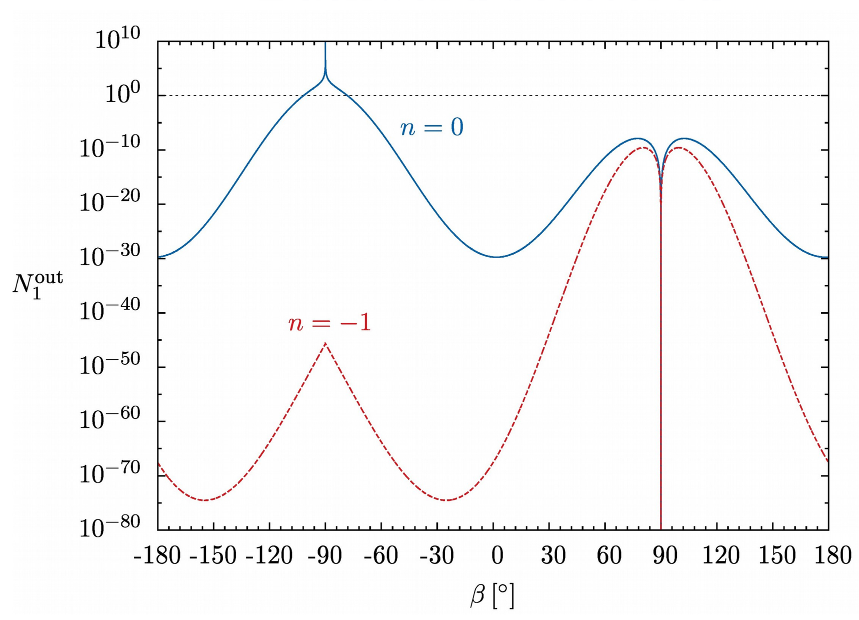
First estimates are obtained by employing generic design parameters of state-of-the-art high-intensity laser facilities:

Design Parameters of POLARIS / JETI200 @ HI Jena
POLARIS: $W = 150\mathrm{J}$, $\tau = 150\mathrm{fs}$, $\lambda = 1035\mathrm{nm}$
JETI200: $W = 4\mathrm{J}$, $\tau = 20\mathrm{fs}$, $\lambda = 800\mathrm{nm}$

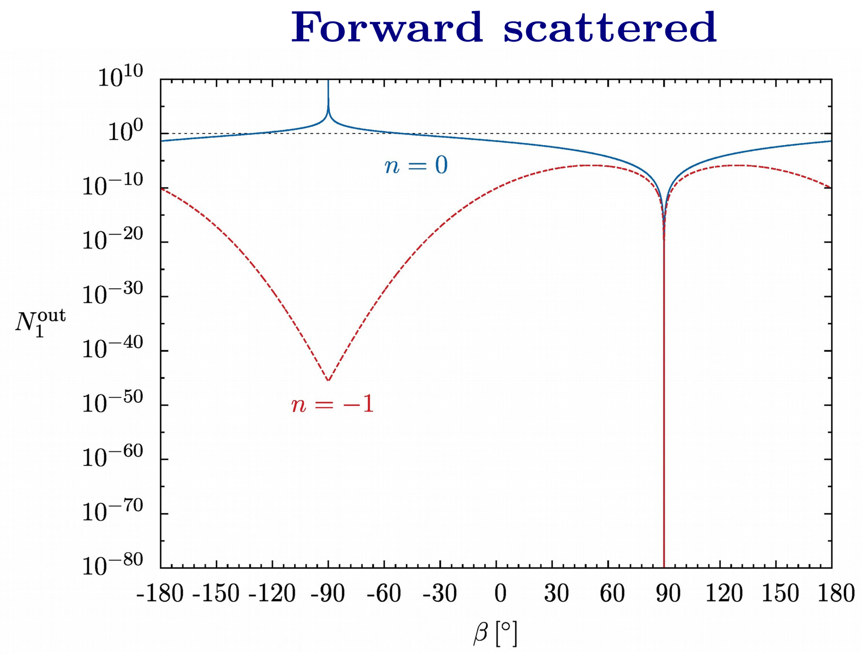
Estimate the number of quantum reflected photons per laser shot via:

$$N^{(\pm)}_{p,2n} \approx R^{(\pm)}_{p,2n}\, N_{\rm in} \approx R^{(\pm)}_{p,2n} \cdot 1.6 \times 10^{19}\ \text{Ph./shot}$$

Backward scattered



Forward scattered



- Maximum scattering for head-on laser pulse collision $\beta = -90°$
- $N^{\rm out} \gtrsim 1$ for incoming angles $-101.79° \leq \beta \leq -78.21°$
- Nontrivial experimental challenge: Advanced techniques required to detect reflection signal (single photon detection, frequency filtering, ...)
- Theoretically: Need to go beyond LCFA to gain insights into polarization properties of scattered probe photons

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