Optical probes of the Quantum Vacuum

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Outline

(i) Introduction: Classical vs. Quantum Vacuum

(ii) Light Propagation in the Quantum Vacuum

"From constant to inhomogeneous fields"

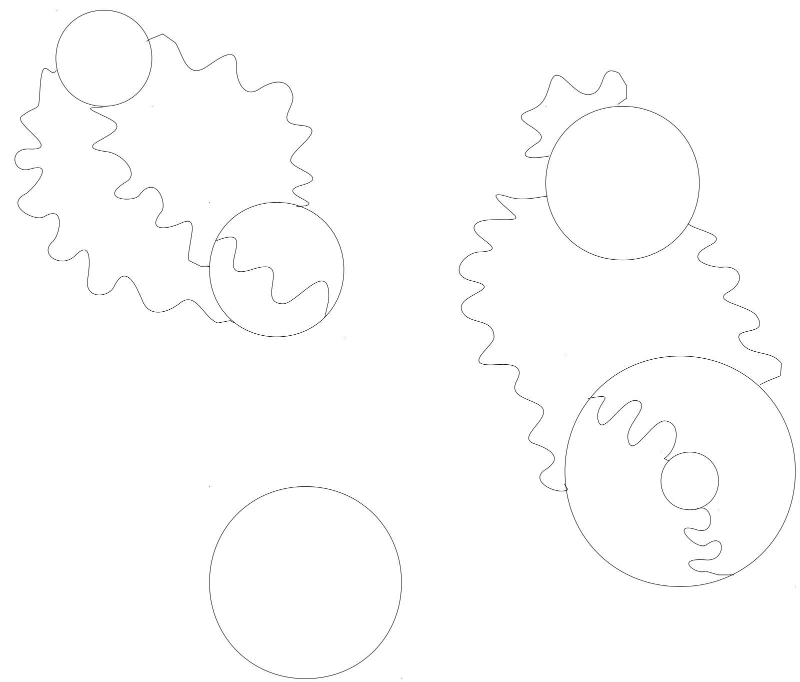
(iii)-(iv) Quantum Reflection

⇒ Basic idea & results

(v) Conclusions and Outlook

(i) Introduction

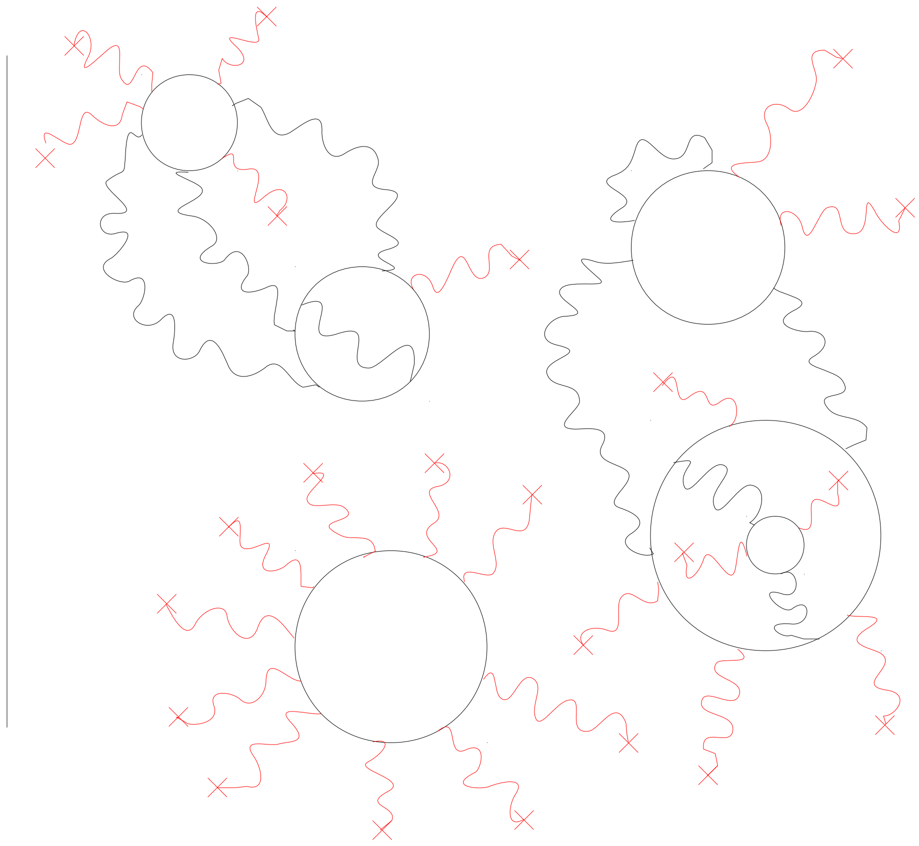
Classical vs. Quantum Vacuum



without external field

(i) Introduction

Classical vs. Quantum Vacuum



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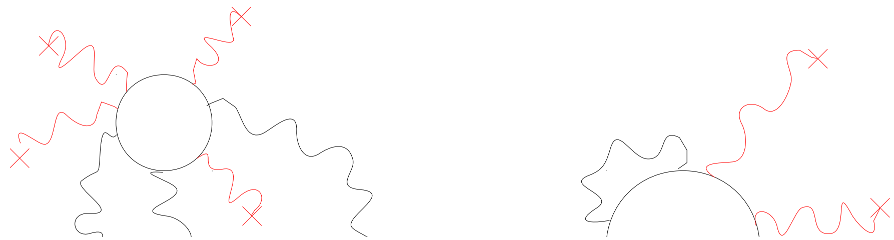
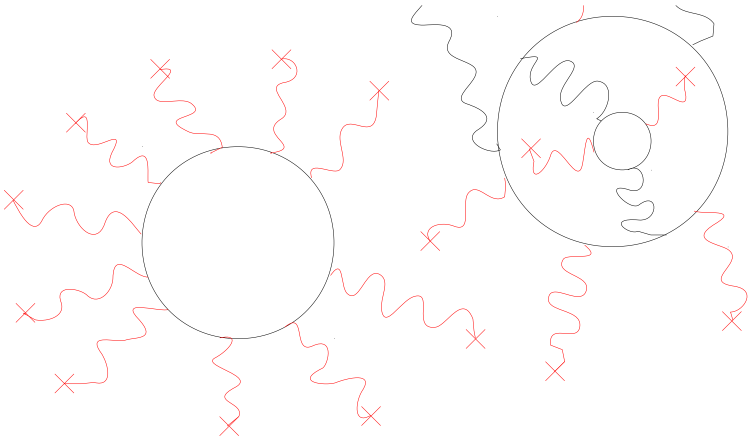


⇒ nonlinear interactions of electro-magnetic fields



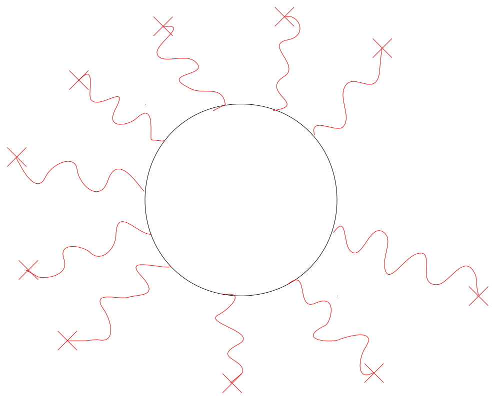
with external field

(i) Introduction

Classical vs. Quantum Vacuum

1-loop diagram
= dominant contribution

diagrams with larger # of
loops suppressed



with external field

[W. Heisenberg & H. Euler, Zeitschr. Phys. **98** (1936)]

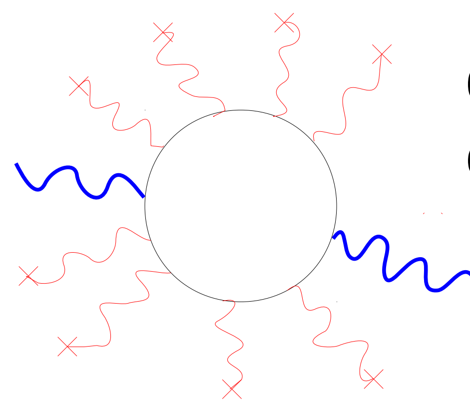
(i) Introduction – Light Propagation

⇔ start with photon / detect photon

Classical vs. Quantum Vacuum

+

[J. S. Toll, PhD Thesis, Princeton (1952)]
[Z. Bialynicka-Birula & I. Bialynicki-Birula, Phys. Rev. D **2** (1970)]



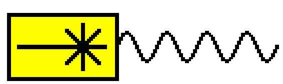
dominant correction

+ ...

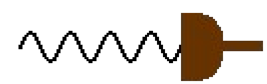
with external field
& probe photons

(ii) Light Propagation in the Quantum Vacuum

$\cong$



start with photon

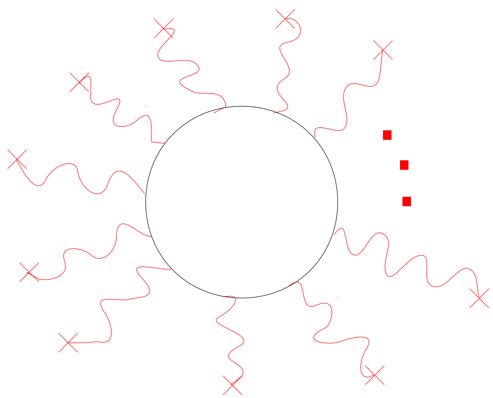


detect photon

(ii) Light Propagation in the Quantum Vacuum

1st step:

[W. Heisenberg & H. Euler, Zeitschr. Phys. **98** (1936)]



1-loop effective action for constant electro-magnetic fields $\mathcal{F}^{\mu\nu}$

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B}) \cdot \frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

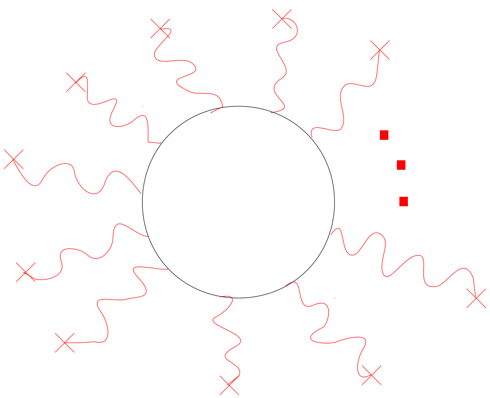
($\mathfrak{E}$, $\mathfrak{B}$ Kraft auf das Elektron.
$|\mathfrak{E}_k| = \frac{m^2 c^3}{e\hbar} = \frac{1}{„137“}\frac{e}{(e^2/mc^2)^2}$ = „Kritische Feldstärke“.)

Ihre Entwicklungsglieder für (gegen $|\mathfrak{E}_k|$) kleine Felder beschreiben Prozesse der Streuung von Licht an Licht, deren einfachstes bereits aus einer Störungsrechnung bekannt ist. Für große Felder sind die hier abgeleiteten Feldgleichungen von den Maxwellschen sehr verschieden. Sie werden mit den von Born vorgeschlagenen verglichen.

(ii) Light Propagation in the Quantum Vacuum

1$^{\rm st}$ step:

[W. Heisenberg & H. Euler, Zeitschr. Phys. **98** (1936)]



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$\left(\begin{array}{l}\mathfrak{E}, \mathfrak{B} \quad \text{Kraft auf das Elektron.} \\ |\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{„137“}\frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“.}\end{array}\right)$

1-loop effective action for constant electro-magnetic fields $\mathcal{F}^{\mu\nu}$

$$\lambda_c = \frac{\hbar}{mc} = 3.9 \times 10^{-13}\mathrm{m}$$

(ii) Light Propagation in the Quantum Vacuum

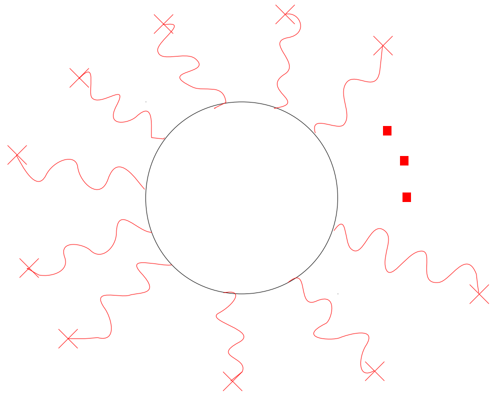
1st step:

[W. Heisenberg & H. Euler, Zeitschr. Phys. **98** (1936)]

Decomposition:

$$\mathcal{F}^{\mu\nu} = F^{\mu\nu} + f^{\mu\nu}$$

in background field ("pump")
& probe photons ("probe").



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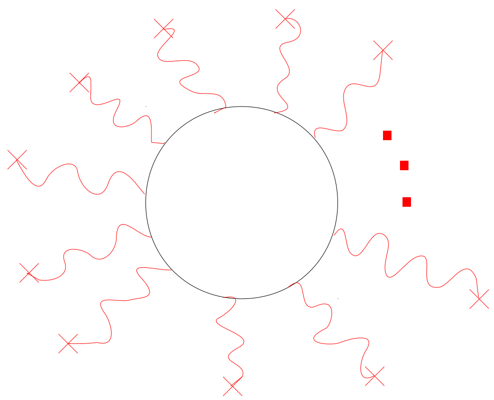
order ($f^{\mu\nu}$)°:



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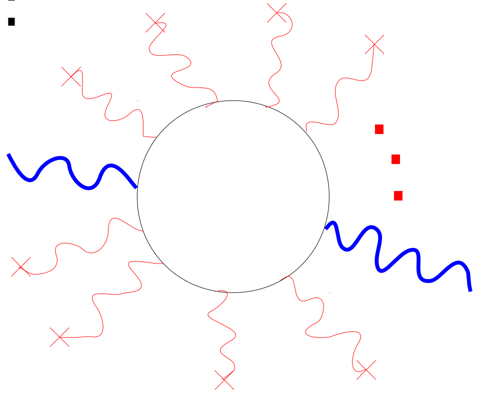

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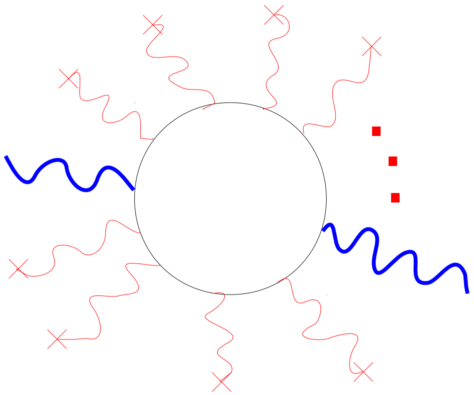
⇔ So far: analytical insights into

- constant background field ("pump")
- propagation of soft probe photons



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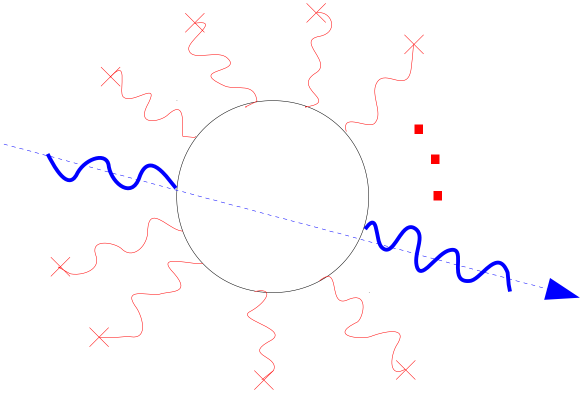
2nd step: propagation of probe photons of arbitrary frequency

explicitly allow for momentum transfer



(ii) Light Propagation in the Quantum Vacuum

2nd step ⇔ generalization of Heisenberg-Euler result to probe photons at arbitrary frequency:

$$\mathcal{L}_{\mathrm{eff}}[\mathcal{A}] = -\frac{1}{4}\mathcal{F}_{\mu\nu}(x)\mathcal{F}^{\mu\nu}(x) - \frac{1}{2}\int_{x'} a_\mu(x)\Pi^{\mu\nu}(x,x'|F)a_\nu(x')\,,$$

with photon polarization tensor $\Pi^{\mu\nu}(x,x'|F)$, analytically known in momentum space at 1-loop order for constant "pump",

[I. A. Batalin & A. E. Shabad, Sov. Phys. JHEP **33** (1971)]

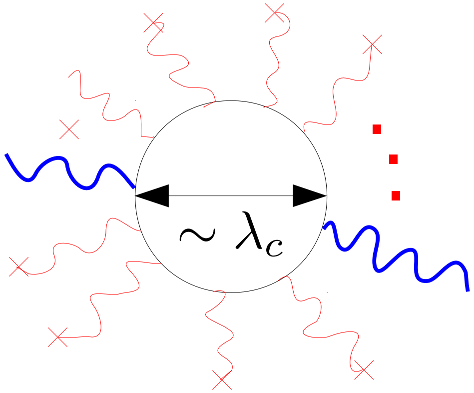
$$\Pi^{\mu\nu}(x,x'|F=const.) = \Pi^{\mu\nu}(x-x'|F) \quad \leftrightarrow \quad \Pi^{\mu\nu}(k|F)\,.$$

4-momentum transfer

(ii) Light Propagation in the Quantum Vacuum

3^{rd} step: towards inhomogeneous "pump" fields.

In position space, the photon polarization tensor probes distances of $\mathcal{O}(\lambda_c = \hbar/(mc) = 3.9 \cdot 10^{-13}\mathrm{m})$.



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⇔ for inhomogeneities with typical variation $w \gg \lambda_c$, it is well justified to use constant field expressions locally.

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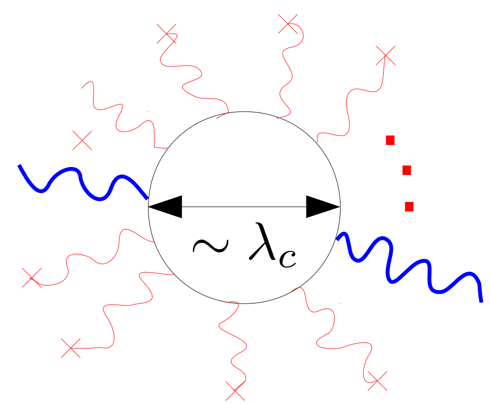

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⇒ schematically:

$$\Pi^{\mu\nu}(k|B = const.) \xrightarrow{\text{F.T.}} \Pi^{\mu\nu}(x - x'|B = const.)$$
$$\xrightarrow{B \to B(x)} \Pi^{\mu\nu}(x, x'|B) \xrightarrow{\text{F.T.}^{-1}} \Pi^{\mu\nu}(k, k'|B) \,. \qquad (*)$$

(ii) Light Propagation in the Quantum Vacuum

here: 1-dimensional inhomogeneity in x direction

<u>Example 1:</u> [= analytical insights in perturbative weak field regime]

$\Pi^{\mu\nu}(k|B = const.)$ has infinite series expansion (about $eB = 0$),

$$\Pi^{\mu\nu}(k_x|B = const.) = \sum_{n=0}^{\infty} \Pi^{\mu\nu}_{(2n)}(k_x)\,(eB)^{2n}.$$

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$$\Big\downarrow (*)$$

$$\Pi^{\mu\nu}(k_x, k'_x|B) = \sum_{n=0}^{\infty} \Pi^{\mu\nu}_{(2n)}(k'_x) \int \mathrm{d}x\, \mathrm{e}^{i(k_x+k'_x)x}[eB(x)]^{2n},$$

for "arbitrary" field profile $B(x)$, compatible with $w \gg \lambda_c$.

(ii) Light Propagation in the Quantum Vacuum

here: 1-dimensional inhomogeneity in x direction

Example 2: [= analytical insights in full, i.e., in particular also non-perturbative regime]

$\Pi^{\mu\nu}(k|B = const.)$ is of following structure,

$$\Pi^{\mu\nu}(k_x|B = const.) \sim N^{\mu\nu}(k_x)\,\mathrm{e}^{-i\frac{f(k_x)}{eB}}\,.$$

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and in particular for $B(x) = \dfrac{B}{1+\left(\frac{2x}{w}\right)^2}$:

$$\Pi^{\mu\nu}(k_x, k'_x|B) = \left|\frac{w}{2}\right| \sqrt{\frac{\pi e B}{i f(k'_x)}} \, N^{\mu\nu}(k'_x) \, \mathrm{e}^{-\frac{i f(k'_x)}{eB} - \frac{eB}{i f(k'_x)}\left(\frac{w}{2}\right)^2 \left(\frac{k_x+k'_x}{2}\right)^2} \, .$$

(ii) Light Propagation in the Quantum Vacuum

Summing up:

⇒ Equations of motion for probe photons a_μ at arbitrary frequency ω in inhomogeneous pump fields $F^{\mu\nu}$, with typical scale of variation $w \gg \lambda_c$.

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⇒ in momentum space:

$$\left(k^2 g^{\mu\nu} - k^\mu k^\nu\right) a_\nu(k) = -\int_{k'} \underbrace{\frac{\Pi^{\mu\nu}(-k,k'|B) + \Pi^{\mu\nu}(k',-k|B)}{2}}_{\equiv \tilde{\Pi}^{\mu\nu}(-k,k'|B)} a_\nu(k') \,.$$

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⇔ simpler scalar equations with the help of projectors (on modes "*p*" polarized $\parallel$ & $\perp$ to plane spanned by $\vec{B}$ & $\vec{k}$).

(ii) Light Propagation in the Quantum Vacuum

Equations of motion for (probe) photon propagation in the Quantum Vacuum subject to strong (E)M fields:

$$k^2 a_p(k) = -\int_{k'} \tilde{\Pi}_p(-k, k'|B)\, a_p(k')\,.$$

with $p \in \{\|, \perp\}$.

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Experiments $\cong$ perturbative weak field regime:

$$\Pi_p(k, k'|B) \approx \Pi^{(0)}(k, k') + \Pi_p^{(2)}(k, k') \left(\frac{eB}{m^2}\right)^2, \quad (\hbar = c = 1)$$

with $\frac{eB}{m^2} = \frac{B[T]}{4 \times 10^9}$ $\Leftrightarrow$ Multi-TW lasers: $B \sim \mathcal{O}(10^5 - 10^6)\mathrm{T}$.

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For <u>constant</u> magnetic fields: [J. S. Toll, PhD Thesis, Princeton (1952)]

$$\Pi_p(-k, k'|B)\big|_{B=const.} \sim \delta(k - k')\, \Pi_p(k|B),$$

$$\left[k^2 + \Pi_p(k|B)\right]\, a_p(k) = 0, \qquad \begin{Bmatrix} v_\| \\ v_\perp \end{Bmatrix} \approx 1 - \frac{\alpha}{4\pi}\left(\frac{eB}{m^2}\right)^2 \frac{\sin^2[\sphericalangle(\vec{k}, \vec{B})]}{45} \begin{Bmatrix} 14 \\ 8 \end{Bmatrix}.$$

(ii) Light Propagation in the Quantum Vacuum

For inhomogeneous magnetic fields:

incident

$$k^2 a_p(k) = -\int_{k'} \tilde{\Pi}_p(-k,k'|B)\, a_p(k') \ .$$

outgoing

probe photon field

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incident

$$k^2 a_p(k) = \underbrace{-\int_{k'} \tilde{\Pi}_p(-k,k'|B)\, a_p(k')}_{\equiv\, j_p(k|B)} \,.$$

outgoing

probe photon field

\+ impose corresponding physical boundary conditions,

\+ additional assumptions,

⇒ solve with Green's functions,

⇒ dispersive $\Re\left(\Pi^{\mu\nu}\right)$ / absorptive effects $\Im\left(\Pi^{\mu\nu}\right)$.

(ii) Light Propagation in the Quantum Vacuum

The standard nonlinear phenomena “birefringence” and “dichroism” exist in homogeneous <u>and</u> inhomogeneous backgrounds.

There are also signatures with manifestly require inhomogeneous pump field configurations.
⇒ interference effects

[B. King, A. Di Piazza & C. H. Keitel, Nature Photon. **4** (2010) & Phys. Rev. A **82** (2010)]

[D. Tommasini & H. Michinel, Phys. Rev. A **82** (2010)]

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We propose <u>Quantum Reflection</u> as a new signature.

(iii) Quantum Reflection

Quantum Reflection of He_2 Several Nanometers Above a Grating Surface

Bum Suk Zhao,* Gerard Meijer, Wieland Schöllkopf

Quantum reflection allows an atom or molecule to be reflected from a solid before it reaches the region where it would encounter the repulsive potential of the surface. We observed nondestructive scattering of the helium dimer (He_2), which has a binding energy of 10^{-7} electron volt, from a solid reflection grating. We scattered a beam containing the dimer as well as atomic helium and larger clusters, but could differentiate the dimer by its diffraction angle. Helium dimers are quantum reflected tens of nanometers above the surface, where the surface-induced forces are too weak to dissociate the fragile bond.

A neutral atom or molecule approaching a solid surface experiences an attractive force caused by the van der Waals atom-surface interaction potential, as sketched in Fig. 1A. In a classical picture, the particle accelerates toward the surface until it scatters back from the steep repulsive-potential branch. In quantum-mechanical scattering, a wave packet approaching the surface exhibits a nonvanishing reflection coefficient even when it is in the attractive part of the potential. Thus, despite the force acting toward the surface, there is some probability that the particle will reflect tens of nanometers or more above the surface, without ever colliding with the repulsive potential wall. The probability for this counterintuitive effect, termed quantum reflection, even approaches unity in the low-energy limit of the incident particle [e.g., (*1*)]. Quantum reflection from a solid was first observed by Shimizu for ultracold metastable Ne (*2*) and He (*3*) atoms. Later, it was also observed with helium atom beams (*4*, *5*). Here, we demonstrate that quantum reflection allows for nondestructive scattering of extremely fragile helium dimers from a ruled reflection grating.

The van der Waals–bound dimer of two ground-state helium atoms, He_2, is the most fragile ground-state molecule known (*6*, *7*). The bind-

Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany.

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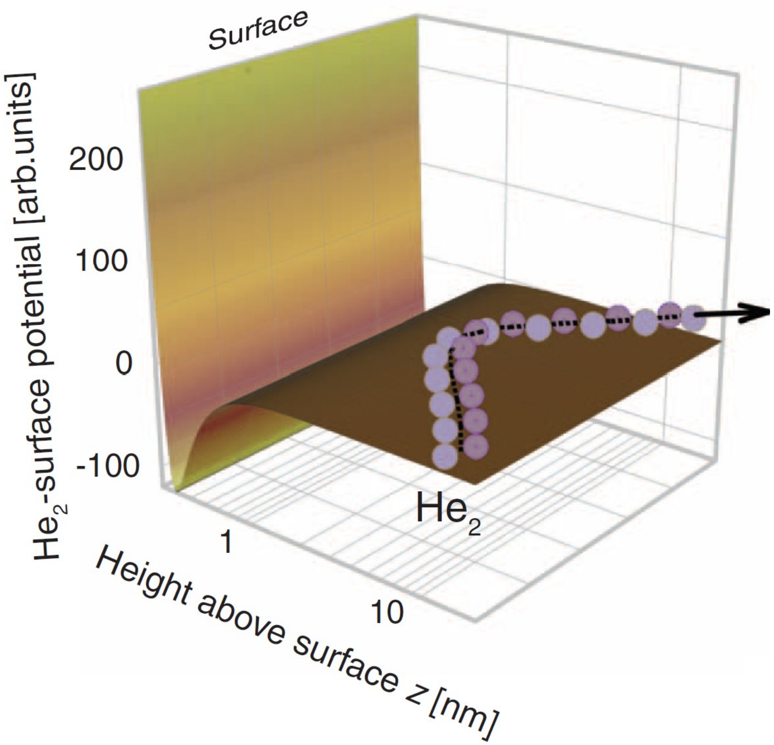

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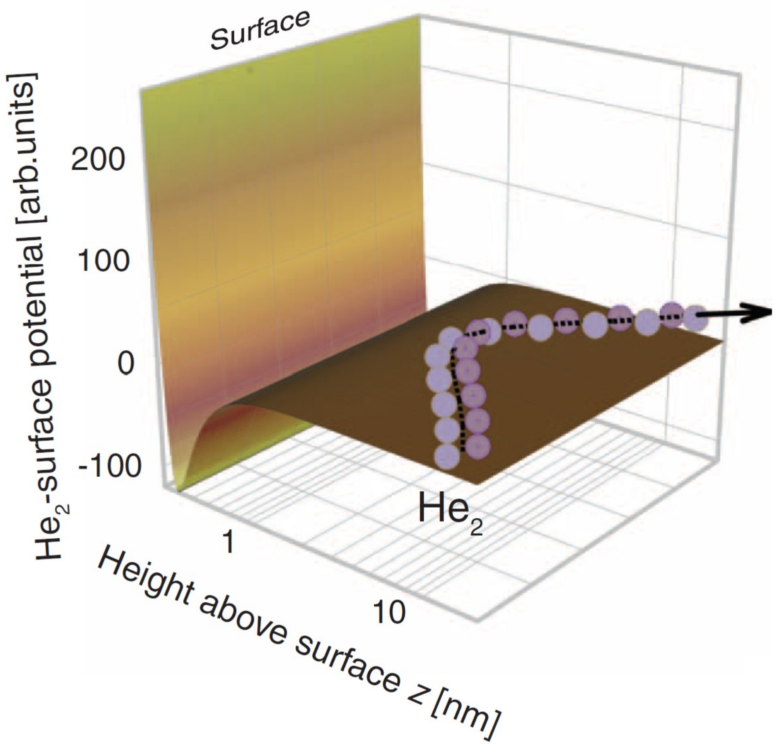


= above-barrier reflection

[V. L. Pokrovskii, et. al., Sov. Phys. JETP **34** (1958)]

18 FEBRUARY 2011 VOL 331 SCIENCE www.sciencemag.org

(iii) Quantum Reflection

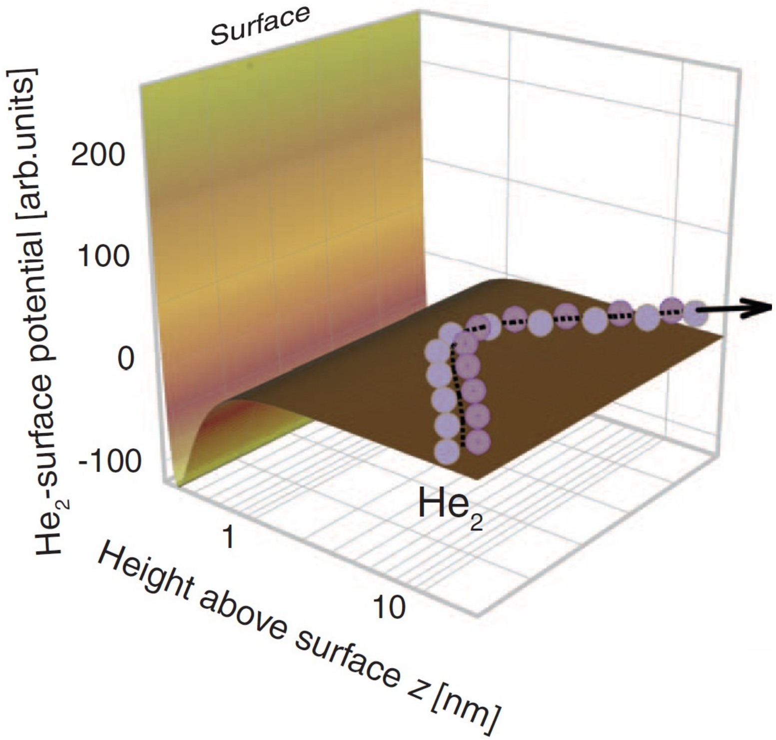
Quantum Reflection of He_2 Several Nanometers Above a Grating Surface

Bum Suk Zhao,* Gerard Meijer, Wieland Schöllkopf

Quantum reflection allows an atom or molecule to be reflected from a solid before it reaches the region where it would encounter the repulsive potential of the surface. We observed nondestructive scattering of the helium dimer (He_2), which has a binding energy of 10^{-7} electron volt, from a solid reflection grating. We scattered a beam containing the dimer as well as atomic helium and larger clusters, but could differentiate the dimer by its diffraction angle. Helium dimers are quantum reflected tens of nanometers above the surface, where the surface-induced forces are too weak to dissociate the fragile bond.

for nondestructive scattering of extremely fragile helium dimers from a ruled reflection grating.

The van der Waals–bound dimer of two ground-state helium atoms, He_2, is the most fragile ground-state molecule known (6, 7). The bind-



atoms ⇔ photons “probe”

surface ⇔ magnetized quantum vacuum “pump”

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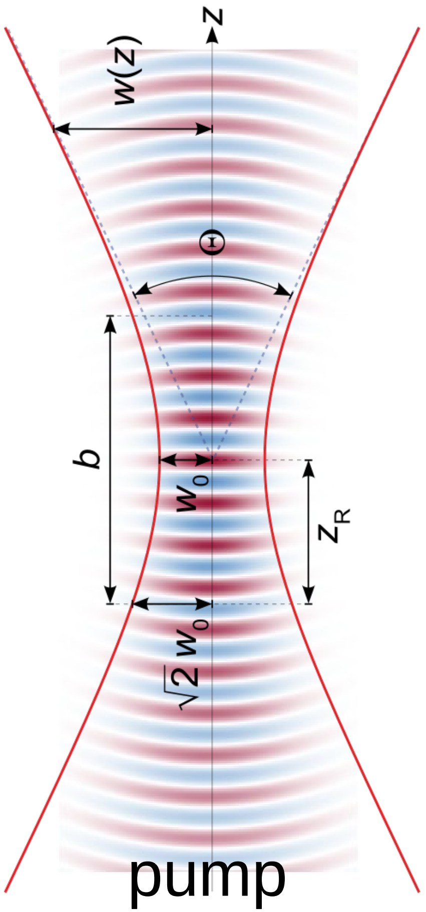
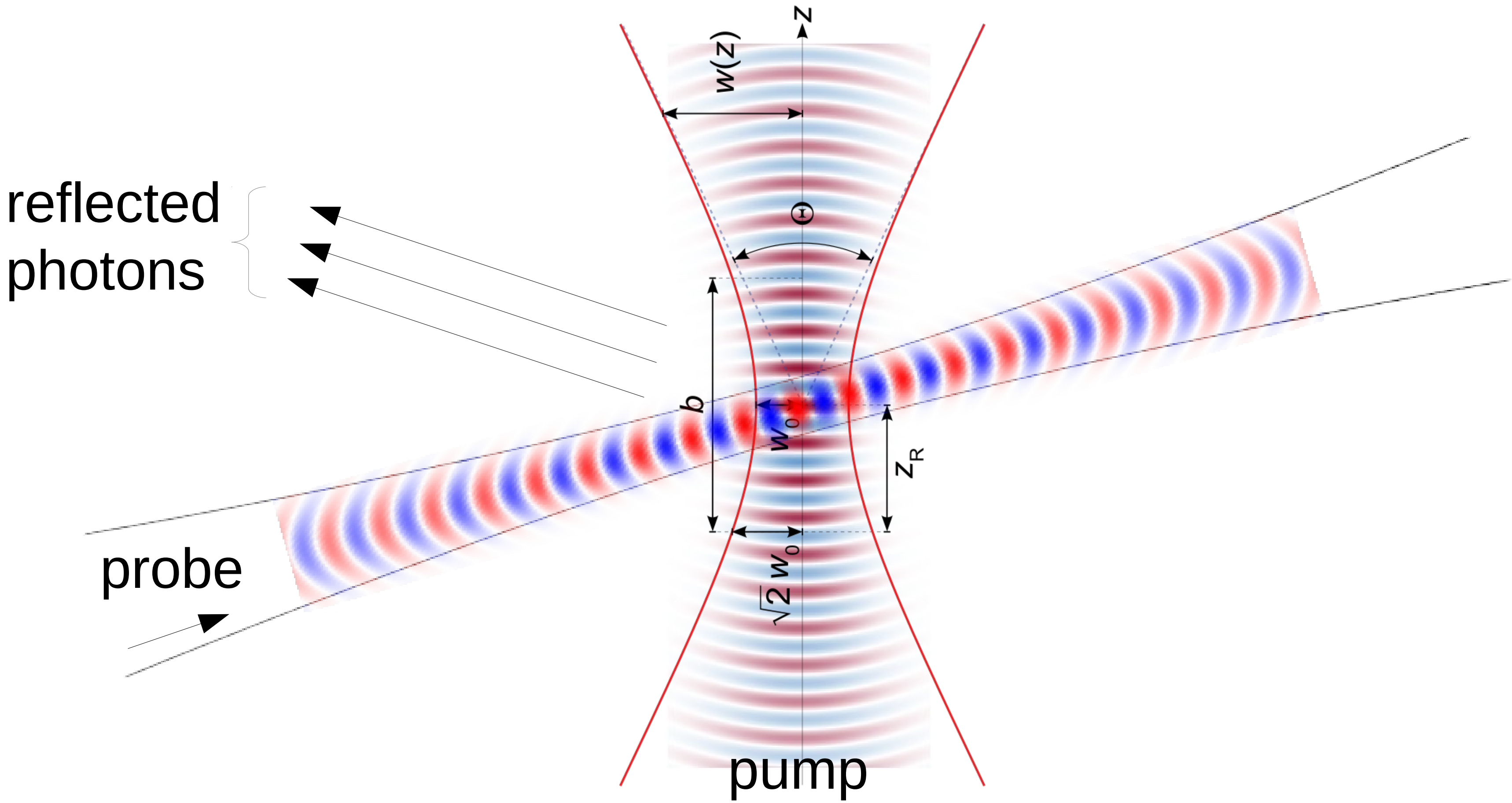
(iii) Quantum Reflection

Consider the scenario: [H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]



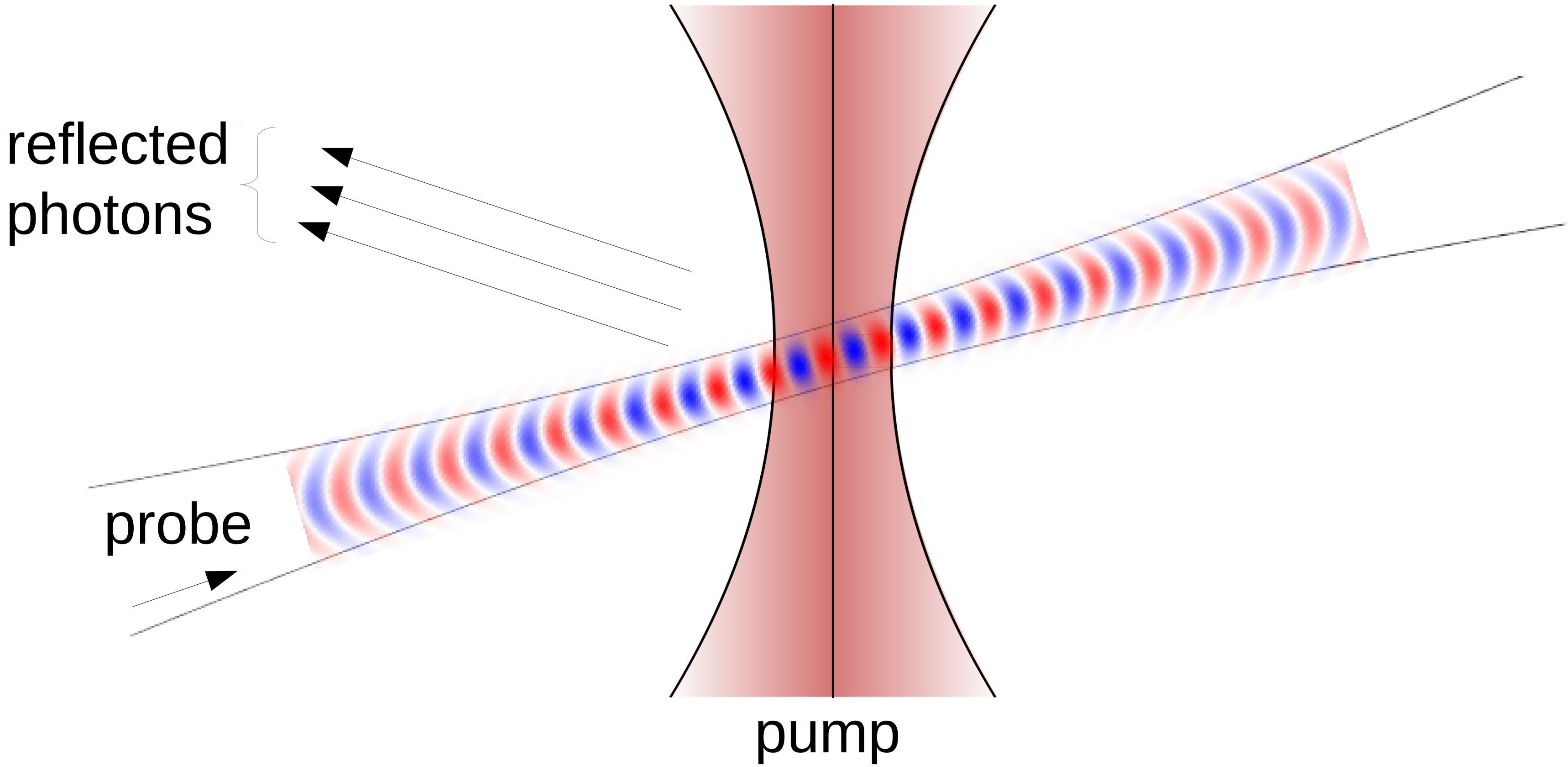
(iii) Quantum Reflection

Consider the scenario: [H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]



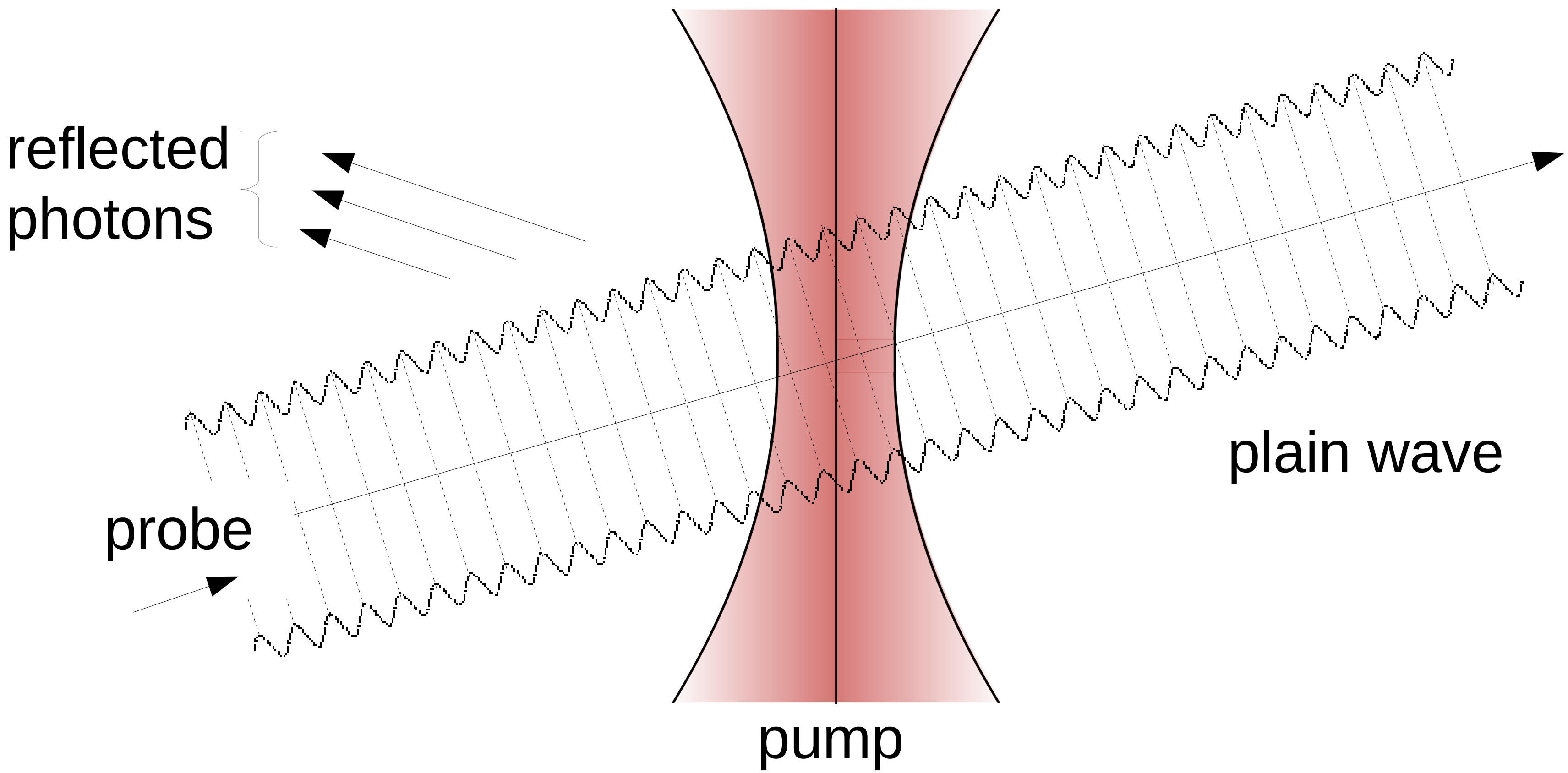
(iii) Quantum Reflection

Consider the scenario: [H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]



(iii) Quantum Reflection

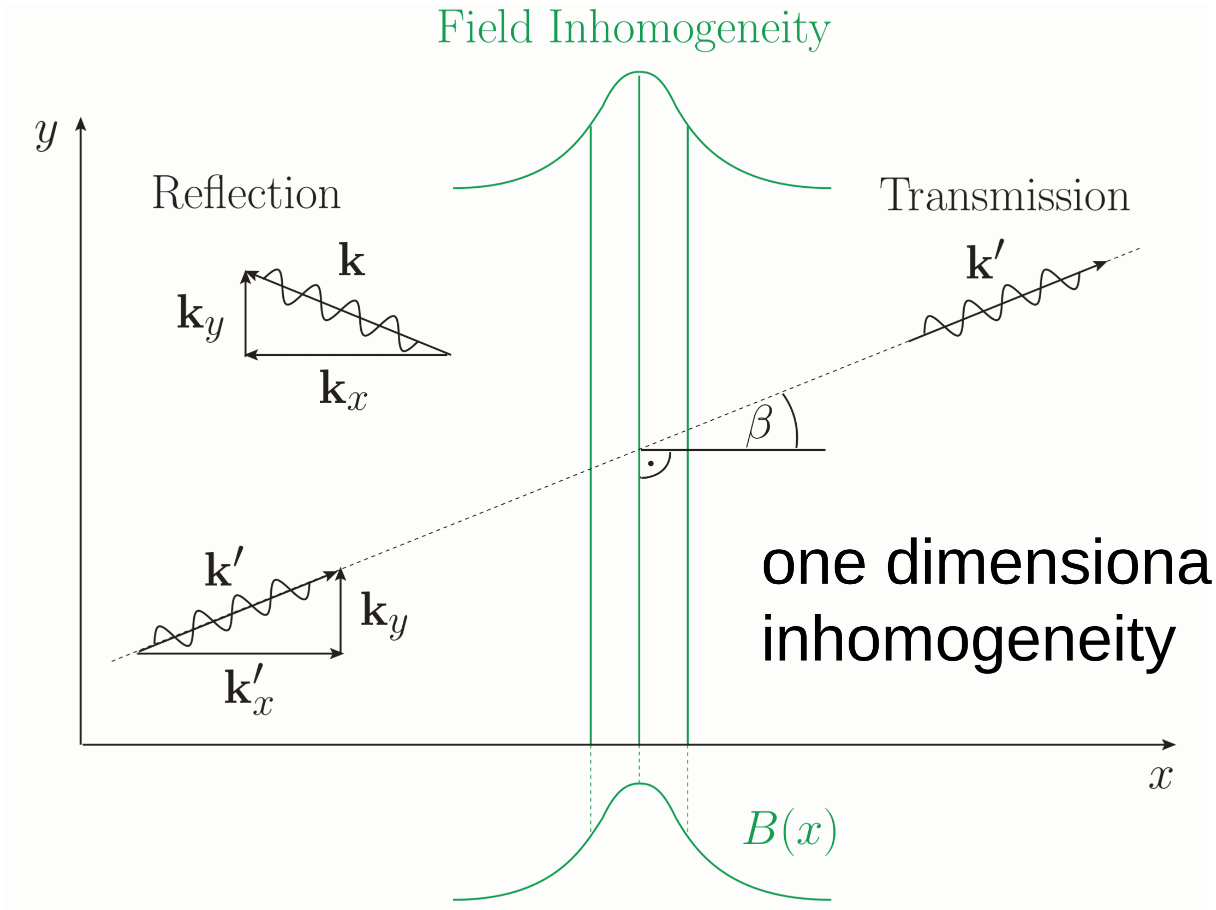
Consider the scenario: [H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]



(iii) Quantum Reflection

Schematically:

[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]



one dimensional spatial inhomogeneity

(iii) Quantum Reflection

Reflection coefficient: (normal incidence):

$$R_p = \left| \frac{\tilde{\Pi}_p(\omega, \omega | B)}{2\omega} \right|^2$$

(iii) Quantum Reflection

In the perturbative weak field regime (normal incidence):

$$R_p = \left| \frac{\tilde{\Pi}_p(\omega,\omega|B)}{2\omega} \right|^2 = \left| \frac{c_p}{\pi}\omega \int \mathrm{d}x\, \mathrm{e}^{i2\omega x} \left(\frac{eB(x)}{m^2} \right)^2 \right|^2 + \mathcal{O}\left((\tfrac{eB}{m^2})^6 \right),$$

with $c_{||} = 7\alpha/90$ and $c_{\perp} = 4\alpha/90$.

(iii) Quantum Reflection

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with $c_{||} = 7\alpha/90$ and $c_{\perp} = 4\alpha/90$.

Can be mapped on QM above-barrier scattering problem:

$$\left(-\frac{d^2}{dx^2} + V(x) \right) a_p(x;\omega) = \omega^2 a_p(x;\omega),$$

with $V(x) = -2\frac{c_p}{\pi}\omega^2 \left(\frac{eB(x)}{m^2} \right)^2 .$

(iv) Results - two different pump profiles

design parameters of high-intensity laser systems to be available in Jena:

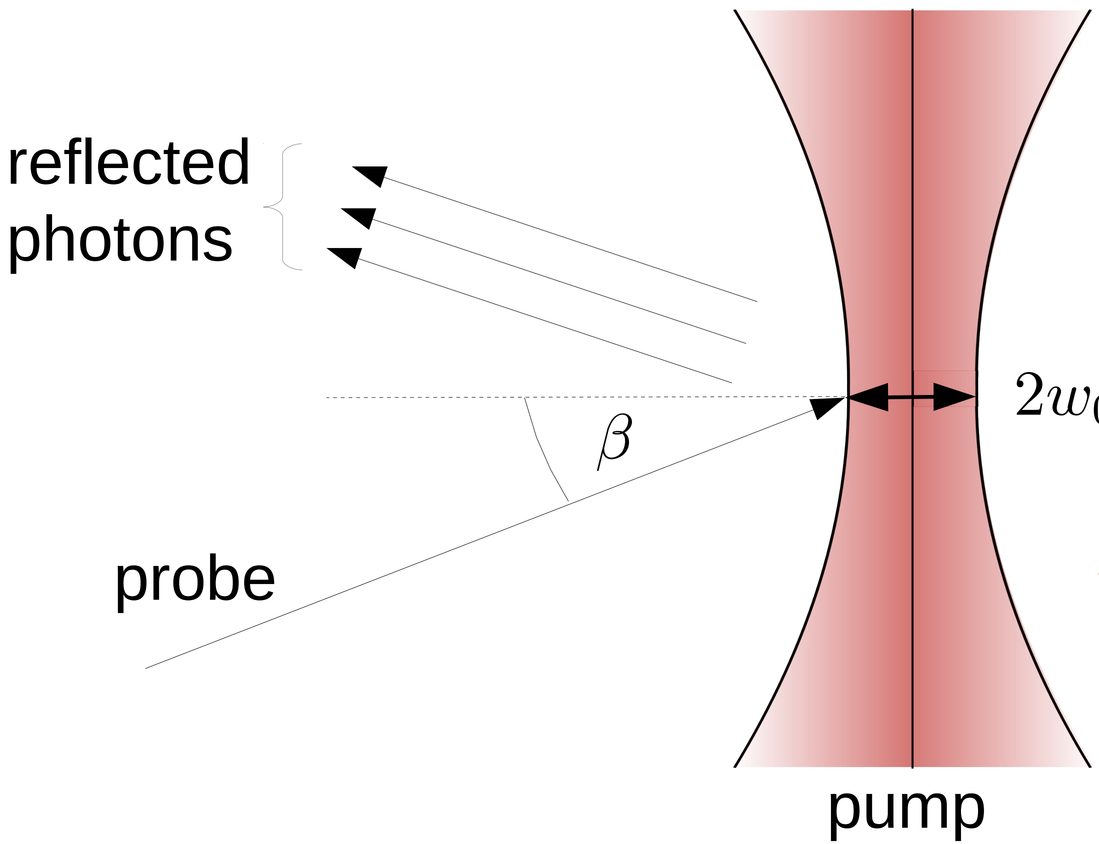
$$\mathrm{POLARIS}: \ \lambda_{\mathrm{pump}} = 1030\mathrm{nm}, \ \mathcal{E}_{\mathrm{pump}} = 150\mathrm{J}, \ \tau_{\mathrm{probe}} = 150\mathrm{fs}$$

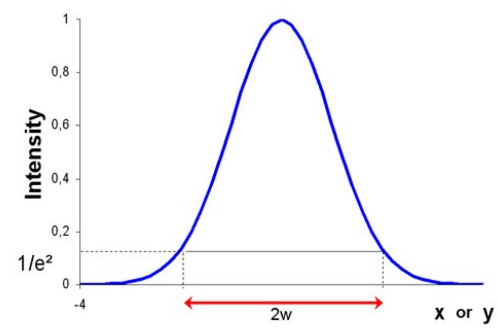
$$\mathrm{JETI\ 200}: \ \lambda_{\mathrm{pump}} = 800\mathrm{nm}, \ \mathcal{E}_{\mathrm{pump}} = 4\mathrm{J}, \ \tau_{\mathrm{probe}} = 20\mathrm{fs}$$

(iv) Quantum Reflection

Scenario (i):

[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]





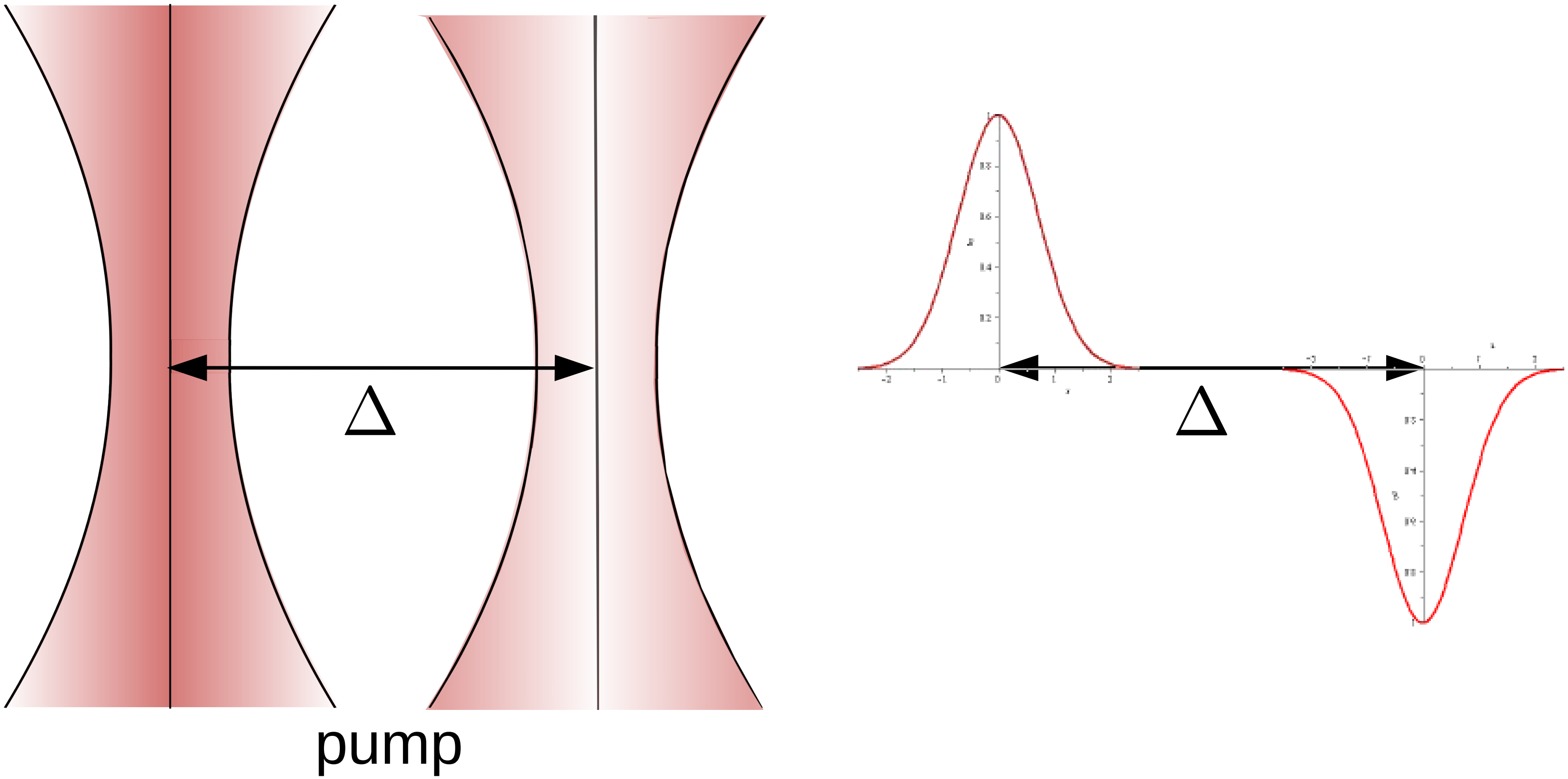
$$2w_0 \approx 2\lambda_{\mathrm{pump}}$$

$$B(x) = B_{\mathrm{pump}}\, \mathrm{e}^{-(x/\lambda_{\mathrm{pump}})^2}$$

(iv) Quantum Reflection

Scenario (ii):

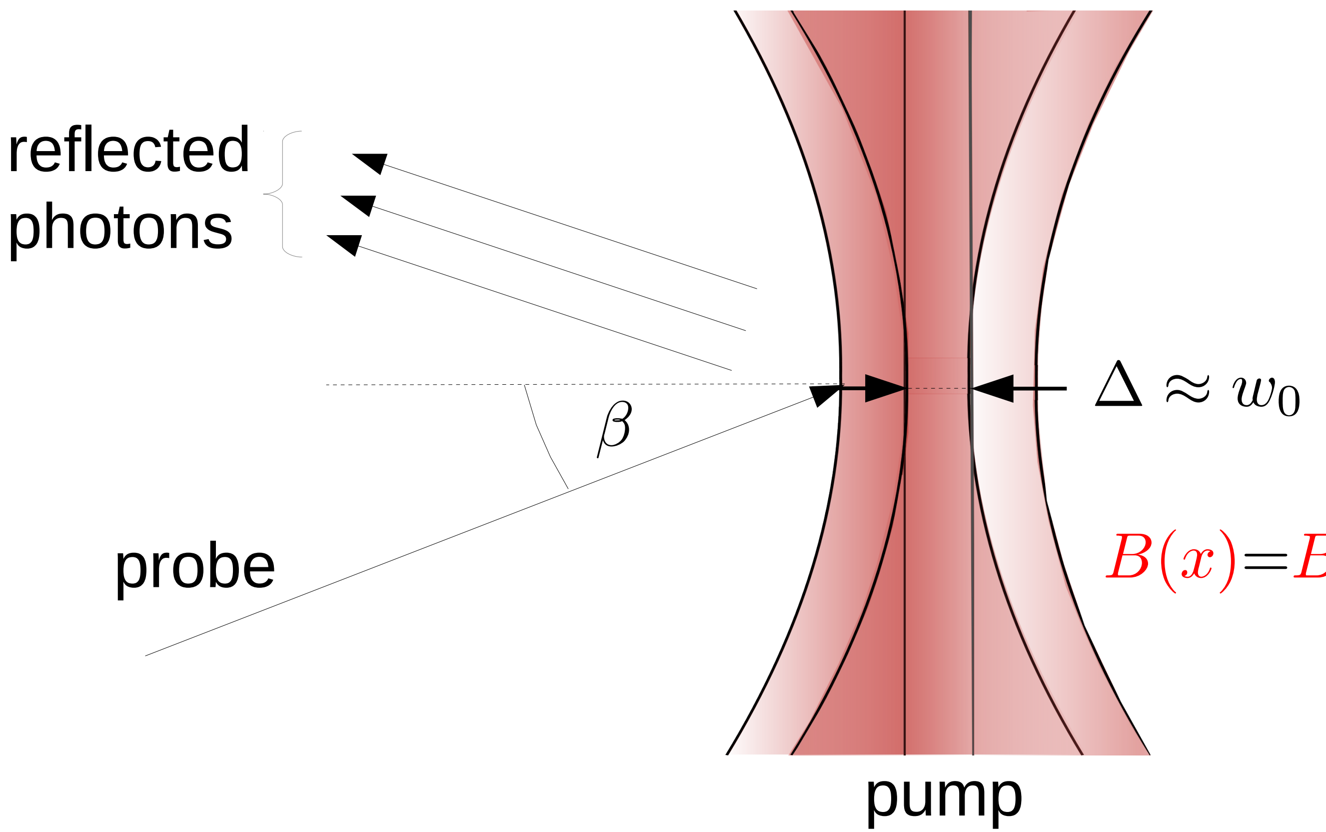
[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]

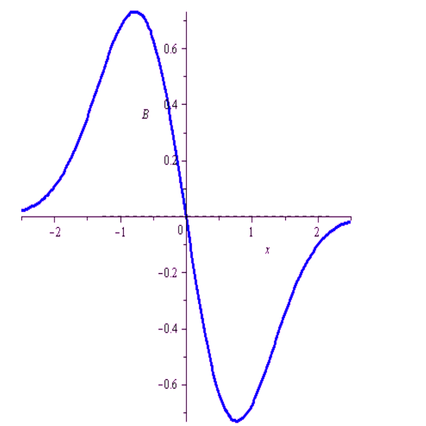


(iv) Quantum Reflection

Scenario (ii):

[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]





$$B(x) = B_{\mathrm{pump}} \mathrm{e}^{-(x/\lambda_{\mathrm{pump}})^2} \times \cos\left(\frac{\pi x}{\lambda_{\mathrm{pump}}} + \varphi\right)$$

(iv) Quantum Reflection

Results:

[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]

⇒ Scenario (i):

$$R_p = \frac{\pi\alpha^2}{4050\cos^2\beta}\left\{\begin{array}{c}49\\16\end{array}\right\}\left(\frac{\lambda_{\rm pump}}{\lambda_{\rm probe}}\right)^2\left(\frac{eB_{\rm pump}}{m^2}\right)^4 \mathrm{e}^{-(2\pi)^2\left(\frac{\lambda_{\rm pump}}{\lambda_{\rm probe}}\cos\beta\right)^2}$$

Number of reflected photons: $N_p = R_p\, N_{\rm probe}$.

(iv) Quantum Reflection

Results: [H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]

⇒ Scenario (i):

$$R_p = \frac{\pi\alpha^2}{4050\cos^2\beta} \left\{ \begin{array}{c} 49 \\ 16 \end{array} \right\} \left(\frac{\lambda_{\mathrm{pump}}}{\lambda_{\mathrm{probe}}} \right)^2 \left(\frac{eB_{\mathrm{pump}}}{m^2} \right)^4 \mathrm{e}^{-(2\pi)^2 \left(\frac{\lambda_{\mathrm{pump}}}{\lambda_{\mathrm{probe}}} \cos\beta \right)^2}$$

Number of reflected photons: $N_p = R_p \, N_{\mathrm{probe}}$.

Maximum for $\cos\beta = \frac{1}{2\pi} \frac{\lambda_{\mathrm{probe}}}{\lambda_{\mathrm{pump}}}$, $\rightarrow \beta \approx 82.9°$

wherefore

$$R_p = \frac{2\pi^3\alpha^2\mathrm{e}^{-1}}{2025} \left\{ \begin{array}{c} 49 \\ 16 \end{array} \right\} \left(\frac{\lambda_{\mathrm{pump}}}{\lambda_{\mathrm{probe}}} \right)^4 \left(\frac{eB_{\mathrm{pump}}}{m^2} \right)^4 . \quad \rightarrow N_p \approx \left\{ \begin{array}{c} 16.00 \\ 5.22 \end{array} \right\}$$

(iv) Quantum Reflection

Results:

[H. Gies, F. K. & N. Seegert, arXiv:1305.2320 [hep-ph]]

⇒ Scenario (ii):

$$R_p \approx \frac{\pi\alpha^2}{64800\cos^2\beta}\left\{\begin{matrix}49\\16\end{matrix}\right\}\left(\frac{\lambda_{\rm pump}}{\lambda_{\rm probe}}\right)^2\left(\frac{e\color{red}{B_{\rm pump}}}{m^2}\right)^4 \mathrm{e}^{-(2\pi)^2\left(\frac{\lambda_{\rm pump}}{\lambda_{\rm probe}}\cos\beta-\frac{1}{2}\right)^2}$$

Number of reflected photons: $N_p = R_p\, N_{\rm probe}$.

Maximum for $\cos\beta = \frac{1}{2}\frac{\lambda_{\rm probe}}{\lambda_{\rm pump}}$, $\color{blue}{\rightarrow\ \beta \approx 67.2^\circ}$

wherefore

$$R_p \approx \frac{\pi\alpha^2}{16200}\left\{\begin{matrix}49\\16\end{matrix}\right\}\left(\frac{\lambda_{\rm pump}}{\lambda_{\rm probe}}\right)^4\left(\frac{e\color{red}{B_{\rm pump}}}{m^2}\right)^4 \qquad \color{blue}{\rightarrow\ N_p \approx \left\{\begin{matrix}0.28\\0.09\end{matrix}\right\}}$$

(v) Conclusions and Outlook

(v) Conclusions and Outlook

We have studied Light Propagation in the quantum vacuum subject to (in)homogeneous (E)M pump fields.

We have proposed Quantum Reflection as new signature of the nonlinearity of the quantum vacuum in strong electro-magnetic (laser) fields.

As our study manifestly builds on Fourier transformations, it was essential to take into account the full momentum dependence.

The end ...

Thank you for your attention!