Backward Compton Scattering in Strong Uniform Magnetic Field

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Abstract

In strong uniform magnetic field, the vacuum Non-Commutative Plane (NCP) caused by the lowest Landau level (LLL) effect and the QED with NCP (QED-NCP) are studied. Being similar to the theory of Quantum Hall effect, an effective filling factor $f(B)$ is introduced to character the possibility that the electrons stays on LLL. The backward Compton scattering amplitudes of QED-NCP are derived, and the differential cross sections for the process with polarized initial electrons and photons are calculated. The existing Spring-8’s data has been analyzed primitively and some hints for QED-NCP effects are shown. We propose to precisely measure the differential cross sections of the backward Compton scattering in perpendicular magnetic field experimentally, which may lead to reveal the effects of QED-NCP.

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I. INTRODUCTION

The physics related to the lowest Landau level (LLL) and the corresponding non-commutative quantum field theory (NCQFT) have long been studied with considerable interests. Considering a charged particle in a uniform magnetic field, the non-relativistic Lagrangian is

\[ L = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \frac{e}{c} (\dot{x}A_x + \dot{y}A_y + \dot{z}A_z). \]  

(1)

Here \( \nabla \times \vec{A} = B\hat{y} \), and the gauge is chosen as \( \vec{A} = (0, 0, -xB) \). Then, solving the corresponding Schrödinger equation, we get the energy eigenvalues of the Landau Levels [1]:

\[ E_n = \hbar eBmc(n + \frac{1}{2}). \]  

(2)

Since the separation between the energy levels is \( O(B/m) \), when the magnetic field is very strong, the separation becomes very large, and consequently only the lowest Landau level (LLL) is relevant. From Eq. (1), the LLL Lagrangian reads

\[ L_{LLL} = -\frac{e}{c} Bxz - V(x, z), \]  

(3)

and then by quantum principle we have

\[ p_z \equiv \frac{\partial L_{LLL}}{\partial \dot{z}} = -\frac{eB}{c} x \Rightarrow \left[-\frac{eB}{c} x, z \right] = -i\hbar \Rightarrow [x, z] = i\frac{\hbar c}{eB} \equiv i\theta_L, \]  

(4)

where \( \theta_L = \frac{\hbar}{eB} \) is a parameter to describe the non-commutativity between space coordinates originated from LLL. It is essential that the last equation in (4) indicates that there is a Non-Commutative Plane \((x, z)\) (NCP) in the 3-dimensional space under very strong \(B\) field. The NCP is perpendicular to the external magnetic field \(B\). Nevertheless, we should note that the physical meaning of the NCP here is irrelevant with that in string/M theory [2, 3, 4], which belongs to the Planck scale physics, even though the mathematic formulations for both of them are similar.

The existence of NCP has been widely used to discuss the quantum Hall effect and relevant topics in the condensed matter physics and the mathematical physics [5, 6, 7, 8, 9, 10]. In such discussions on quantum Hall effects, the non-commutative parameter for the NCP is usually taken to be

\[ \theta = f\theta_L, \]  

(5)

where factor \( f = f(\nu, B) \) is a function of filling factor \( \nu \) and \( B \) field.
A nature question arisen from the condensed matter physics discussions mentioned above is whether such sort of NCP discussions can be extended into the vacuum QED. As a matter of fact (see Ref. [11]), the anomalous deviation of \((g-2)\)-factor of muon to the prediction of the standard model has been attributed to the loop effects of the QED with NCP, i.e., a kind of Non-Commutative QED. That could be thought as a rough estimation of NCP effects in QED at loop level. There are some uncertainties in such \((g-2)\) studies both due to theoretical treatment errors and due to experiment measure errors. An exploration to NCP effects in QED at tree level in the accelerator experiments could be essential to make the thing clear. The motivation of this letter is to pursue the backward Compton scattering process in the strong magnetic field which is a QED process on NCP at tree level, and to explore whether NCP effects exist or not.

At the first glance, since \(\text{e}\gamma\)-Compton scattering at low energy is a typical quite well understanding process in QED and has been widely studied for more than 80 years, it seems hopeless to get any new subtle information from it nowadays. However, to the best of our knowledge, the \(\text{e}\gamma\)-scattering inside a perpendicular strong magnetic field haven’t been studied precisely in experiments until now, therefore such a study may reveal some signal of NCP effects in QED.

The point for revealing NCP effects caused by the LLL effect in a process is that the external perpendicular magnetic field \(B\) “felt” by the electron with non-relativistical motion should be very strong. We would like to address that the backward Compton scattering experiment can finely satisfy this precondition. The backward Compton scattering is a process that the soft laser photon is back scattered by high energy electron elastically. In the \(\text{e}\gamma\)-mass center frame (CM), the motion of the electron is non-relativistic, the Lorentz factor to the laboratory frame is very large and the magnetic field “felt” by the electron \(B = B_{CM} = \gamma B_{Lab}\) becomes very large even if \(B_{Lab}\) is small. For instance, in the beamline BL38B2 in Spring-8 accelerator with 8GeV electron and 0.01eV photon, the velocity of the electron \(v_{CM} \simeq 0.0006 \ll 1, \gamma \simeq 15645.6, B_{Lab} \simeq 0.117T, B_{CM} \simeq 1827T\). It finely satisfies the precondition, hence the NCP due to LLL can be described by constructing a non-commutative quantum theory in the mass center frame.

In this letter, we are going to derive the differential cross section of the backward Compton scattering in a uniform magnetic field. The QED with NCP will be constructed and employed. We expect that a precise measurement of this differential cross section will lead
to distinguish the prediction of QED with NCP from the prediction of QED without NCP.

II. QED WITH NON-COMMUTATIVE PLANE

Non-Commutative Quantum Field Theory (NCQFT) was formulated several years ago by considering a definite limit of string theory with a nonzero background “magnetic” field \([2, 3, 4]\). In natural units \(\hbar = c = 1\), the Lagrangian of Non-Commutative QED (NCQED) is

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} \star F^{\mu\nu} + \bar{\psi} \star (i\gamma^\mu D_\mu - m) \star \psi,
\]

(6)

with

\[
D_\mu = \partial_\mu - ieA_\mu, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ie[A_\mu, A_\nu],
\]

(7)

and \(\star\) means the Moyal product:

\[
(f \star g)(x) = \lim_{\xi, \eta \to 0} \left[ e^{i\theta_{\mu\nu}\partial_x^\mu \partial_\eta^\nu} f(x + \xi)g(x + \eta) \right],
\]

(8)

where

\[
\left[ \hat{x}_\mu, \hat{x}_\nu \right] = i\theta_{\mu\nu} = i\theta C_{\mu\nu}, \quad \theta = f\theta_L = f \frac{1}{eB},
\]

(9)

\[
C_{\mu\nu} = \begin{pmatrix}
0 & c_{01} & c_{02} & c_{03} \\
-c_{01} & 0 & c_{12} & -c_{13} \\
-c_{02} & -c_{12} & 0 & c_{23} \\
-c_{03} & c_{13} & -c_{23} & 0
\end{pmatrix}
\]

(10)

and \(f = f(B)\) could be thought as an effective filling factor to be determined experimentally.

We are interested in the NCQED whose non-commutative behaving only emerges on a NCP, i.e., the QED with NCP (QED-NCP). In this letter, we calculate in the mass center frame, in which the motion of the electron is non-relativistic. In the laboratory frame the direction of the external magnetic field is \(\hat{y}\). By means of the Lorentz transformation, in the mass center frame the electron feels an electric field along \(-\hat{x}\) and a magnetic field along \(\hat{y}\). The electric field has no influence to the non-commutativity caused by the LLL \([9]\), so that \(c_{0i} = 0\). The magnetic field is along \(\hat{y}\) and the NCP takes \((x, z)\)-plane, so that \(c_{13} = 1\) and other \(c_{ij} = 0\).

Note that when one investigated the inverse Compton scattering by external electromagnetic field or the synchrotron radiation, the \(A_\mu\) in the Lagrangian of QED-NCP should be
replaced by $A_\mu + A_\mu^{\text{external}}$. Because we do not study that process in this letter, but only interest in the Compton scattering process, the $A_\mu^{\text{external}}$ is neglected.

III. BACKWARD COMPTON SCATTERING IN THE MAGNETIC FIELD

The backward Compton scattering in the magnetic field is a process that the soft laser photon is back scattered by high energy electron elastically. Similar to the existed calculations of Compton scattering in NCQED [12], we use QED-NCP to calculate the scattering. The Feynman rules, Feynman diagrams, kinematics and the differential scattering cross section for backward Compton scattering are as follows:

1. From the Lagrangian [6], the Feynman rules for QED-NCP are shown in Fig.1. The propagators for electron and photon are the same as QED.

   a) $ie\gamma^\mu \exp(ip_1\theta p_2/2)$

   b) $2e \sin(k_1\theta k_2/2)((k_1 - k_2)^\rho g^{\mu \nu} + (k_2 - k_3)^\nu g^{\rho \mu} + (k_3 - k_1)^\mu g^{\rho \nu})$

   FIG. 1: Feynman rules

2. The Feynman diagrams of $e\gamma$-Compton scattering in QED-NCP are shown in Fig.2. $A(i)$ with $i = 1, 2, 3$ denote the amplitudes of corresponding diagrams. Comparing with that in QED, there is an additional diagram $A(3)$ (see Fig.2(c)).

3. Kinematics (see Fig.3):

   i) The energies and momenta in the mass center frame:

   $$s = (p_1 + k_1)^2, \quad t = (p_1 - p_2)^2, \quad u = (p_1 - k_2)^2,$$
ii) Polarizations: We are interested in the process with polarized initial electrons, unpolarized or $\alpha$-polarized initial photons ($\alpha$ is the angle between initial photon polarization and magnetic field), unpolarized final electrons and unpolarized final photons. So that the following notations and formulas will be useful for our goal:

1) initial electron:

$$u^{-1/2}(p_1)\bar{u}^{-1/2}(p_1) \rightarrow \rho = \frac{1}{2}(\gamma_1 + m)(1 - \gamma^5(-1)\gamma^2)$$
2) final electron:
\[
\sum_i u^i(p_2) \bar{u}^i(p_2) \rightarrow \rho' = p_2 + m
\]
3) photon polarization sums:
\[
g_{\mu\nu} = \epsilon_{\mu}^+ \epsilon_{\nu}^+ + \epsilon_{\mu}^- \epsilon_{\nu}^- - \sum_i \epsilon_i^T \epsilon_i^{T^*}
\]
\[
\epsilon_{\mu}^+(k) = \left(\frac{k^0}{\sqrt{2|\vec{k}|}}, -\frac{\vec{k}}{\sqrt{2|\vec{k}|}}\right), \quad \epsilon_{\mu}^-(k) = \left(\frac{k^0}{\sqrt{2|\vec{k}|}}, \frac{\vec{k}}{\sqrt{2|\vec{k}|}}\right)
\]
4) initial photon:
\[
\epsilon_{\alpha\mu}^T = (0, \sin \alpha, \cos \alpha, 0), \quad \epsilon_{\alpha\mu}^T = (0, 1, 0, 0), \quad \epsilon_{\nu\mu}^T = (0, 0, 1, 0),
\]
unpolarized: \[\frac{1}{2} \sum_i \epsilon_{\mu}^T(k_1) \epsilon_{i\mu}^{T^*}(k_1) \rightarrow \xi_{\mu\nu}\]
\[
\alpha - \text{polarized}: \epsilon_{\alpha\mu}^T(k_1) \epsilon_{\alpha\mu}^{T^*}(k_1) \rightarrow \xi_{\mu\nu}
\]
5) final photon:
unpolarized: \[\sum_i \epsilon_{i\nu}^T(k_2) \epsilon_{i\nu}^{T^*}(k_2) \rightarrow \xi'_{\nu\omega}\]

4. Differential cross sections for backward Compton scattering in QED-NCP are as follows
\[
\frac{d\sigma}{d\phi d\cos \theta} = \frac{e^4}{64\pi^2(s + m^2)^2} \xi_{\mu\nu} \epsilon_{\nu\omega}^T Tr(\rho' A p A)
\]
where \(A = A(1) + A(2) + A(3)\) and \(A(i)|_{i=1,2,3}, \ A(i)|_{i=1,2,3}\) are:
\[
A(1) = (-1) e^{i p_1 \theta_2 / 2} e^{i k_1 \theta_2 / 2} \mu \left(\frac{\gamma_1 + m}{(p_1 + k_1)^2 - m^2} \gamma_\nu \right)
\]
\[
A(2) = (-1) e^{i p_1 \theta_2 / 2} e^{-i k_1 \theta_2 / 2} \mu \left(\frac{\gamma_1 - m}{(p_1 - k_2)^2 - m^2} \gamma_\nu \right)
\]
\[
A(3) = (-i) e^{i p_1 \theta_2 / 2} 2 \sin(k_1 k_2 / 2) \left((k_1 + k_2)^\rho g^{\mu\nu} + (k_1 - k_2)^\rho g^{\mu\nu} + (k_2 - 2k_1)^\rho g^{\mu\nu} \right)
\]
\[
\bar{A}(1) = (-1) e^{-i p_1 \theta_2 / 2} e^{-i k_1 \theta_2 / 2} \mu \left(\frac{\gamma_1 + m}{(p_1 + k_1)^2 - m^2} \gamma_\nu \right)
\]
\[
\bar{A}(2) = (-1) e^{-i p_1 \theta_2 / 2} e^{i k_1 \theta_2 / 2} \mu \left(\frac{\gamma_1 - m}{(p_1 - k_2)^2 - m^2} \gamma_\nu \right)
\]
\[
\bar{A}(3) = (i) e^{-i p_1 \theta_2 / 2} 2 \sin(k_1 k_2 / 2) \left((k_1 + k_2)^\rho g^{\mu\nu} + (k_1 - k_2)^\rho g^{\mu\nu} \right)
\]

We define the phase factor \(\Delta \equiv \frac{k_1 \theta_2}{2} = -\frac{k_1 \theta_2}{2}\) (notation \(k \theta p \equiv k^\mu \theta_{\mu\nu} \rho^{\nu}\)), and then the differential cross sections of the backward Compton scattering with polarized initial
electrons, unpolarized initial photons, unpolarized final electrons and unpolarized final photons in QED-NCP is:

$$\frac{d\sigma}{d\phi d\cos\vartheta} = \frac{e^4}{32\pi^2(s + m^2)} \left( (s - m^2)^2 + (u - m^2)^2 - \frac{4m^2t(m^4 - su)}{(s - m^2)(u - m^2)} \right) \times \left( - \frac{1}{(s - m^2)(u - m^2)} + \frac{4\sin^2\Delta}{t^2} \right).$$

(12)

Note that as $m \to 0$, it coincides with that in NCQED (see Ref. [12]). Note that it’s $f(B)$ dependent and goes back to that in QED when $f(B) \to 0$. Similarly, for the processes with any polarization, the differential cross sections could be calculated, some numerical results are shown in the next section.

IV. Summary and Outlook

In this letter, the vacuum Non-Commutative Plane (NCP) perpendicular to the magnetic field and the QED with NCP (QED-NCP) are studied. Being similar to the theory of Quantum Hall effect, an effective filling factor $f(B)$ is introduced to characterize the possibility that the electrons stay on the lowest Landau level (LLL). The backward Compton scattering amplitudes of QED-NCP are derived, and the differential cross sections for the process with polarized initial electrons and photons are calculated. We propose to precisely measure the differential cross sections of the backward Compton scattering in the perpendicular magnetic field experimentally, which may lead to reveal the effects of QED-NCP.

To show this proposal is practicable, we finally discuss a measurement of the backward Compton scattering in Spring-8. The accelerator beamline BL38B2 in Spring-8 has a bending magnet light source, 10MeV $\gamma$-ray photons are produced in the magnetic field by backward Compton scattering of FIR laser photons. The energy of electron in the storage ring is 8GeV, the perimeter of the ring is 1436m, the wavelength of FIR laser photon is 119$\mu$m. Then, in the mass center frame, the Lorentz factor $\gamma \equiv 1/\sqrt{1 - v^2} = 15645.6$, the magnetic field is 356867eV$^2$ $\simeq$ 1827T (hence the LLL effect is relevant) and $\theta_L$ is $9.25 \times 10^{-6} eV^{-2} \simeq (6\AA)^2$. We detect final photon in NCP, i.e., $\phi = \pi$, then the phase factor becomes $\Delta = f\theta_L \frac{(s - m^2)^2 \cos\phi \sin\vartheta}{s} \approx 0.4918f\sin\vartheta$. Substituting all of these into Eq. (11), the realistic calculations are doable. In order to compare with the data of Spring-8, the results are transferred to the laboratory frame.
Fig. 4 shows a measurement of the differential cross section to final photon energy of backward Compton scattering in Spring-8. The polarization of initial photon is not clear so far, i.e., it may be unpolarized or linearly polarized. We discuss both cases as follows:

1. Unpolarized Initial Photon in Fig. 4

Suppose the initial photon is unpolarized, from Fig. 4, we can roughly see:

$$R|_{\text{expt}} = \frac{\frac{d\sigma(5\text{MeV})}{dE_\gamma}|_{\text{expt}}}{\frac{d\sigma(9\text{MeV})}{dE_\gamma}|_{\text{expt}}} \approx \frac{0.15}{0.22} \approx 0.68.$$  

However, the QED prediction is (see Fig. 5):

$$R|_{\text{QED}} = \frac{\frac{d\sigma(5\text{MeV})}{dE_\gamma}|_{\text{QED}}}{\frac{d\sigma(9\text{MeV})}{dE_\gamma}|_{\text{QED}}} \approx \frac{3.9}{6.2} \approx 0.63.$$  

We find out that $R|_{\text{expt}}$ is significantly larger than $R|_{\text{QED}}$. A natural interpretation to this deviation is that the possibility that the electrons stays on LLL is nonzero, and there is a NCP in the external magnetic field, which haven’t been taken into account in QED. By means of QED-NCP, and adjusting the effective filling factor $f(B)$, a suitable $R|_{\text{QED-NCP}}$ can be obtained. The corresponding prediction with $f(B) = 2 \times 10^{-4}$,
which is consistent with $R|_{\text{exp}}$, are shown in Fig. 5:

$$R|_{\text{QED-NCP}} = \left. \frac{d\sigma(5\text{MeV})/dE_{\gamma}}{d\sigma(9\text{MeV})/dE_{\gamma}} \right|_{\text{QED-NCP}} \simeq \frac{4.3}{6.3} \simeq 0.68.$$  

![Figure 5: Energy dependence of the differential cross section of unpolarized initial photon.](image)

However, as we carefully study the shapes of the experimental data in Fig. 4 and the QED and QED-NCP predictions in Fig. 5 by normalizing them at $E_{\gamma} = 6$ MeV, Fig. 6 shows that the uncertainties of experimental data are too large to separate two
calculations. In addition, photon polarization, photon polarization direction, detector inefficiencies, and radiation corrections due to mirror and windows will all affect the shapes of experiment data. We realize it is still too early to decide whether there are QED-NCP effects on this experimental data of back Compton scattering. A further precise measurement is needed.

With $f(B) = 2 \times 10^{-4}$, we further consider experiments with polarized initial photon. The initial laser photons move along direction $\hat{z}$ and their polarizations are either perpendicular to or parallel the magnetic field direction $\hat{y}$. The former is $\hat{x}$-polarized and the energy dependence of differential cross section in both QED and QED-NCP are shown in Fig. 7(a). We find out that they are very close to each other. The latter is $\hat{y}$-polarized and the energy dependence of differential cross section in QED and QED-NCP are very different (see Fig. 7(a)). This strongly suggests that the backward Compton scattering experiment in Spring-8 with photon polarization parallel the magnetic field is the most favorable to test the QED-NCP effects.

2. $\alpha$-polarized Initial Photon in Fig. 4

Suppose the initial photon in Fig. 4 is linearly polarized and the solid angle between the initial photon polarization and the magnetic field is $\alpha$. With $\alpha = 7\pi/30$, we can roughly fit the QED prediction of the energy dependence of the differential cross section (see Fig. 8(a)) to the measurement of it in Spring-8 (see Fig. 4). Since

$$R_{\alpha\text{-polarized}}^{QED} = \frac{d\sigma(5\text{MeV})/dE_{\gamma}}{d\sigma(9\text{MeV})/dE_{\gamma}}_{\alpha\text{-polarized}} \approx \frac{4.3}{6.3} \approx 0.68,$$
a more natural interpretation to the deviation between $\mathcal{R}_{QED}$ and $\mathcal{R}_{\text{expt}}$ is that the initial photon is $\alpha$-polarized.

We further consider the ratio of the differential cross section with $\hat{x}$-polarized initial photon to that with $\hat{y}$-polarized initial photon:

$$\mathcal{R}_{QED} = \frac{d\sigma(\hat{x} - \text{polarized})}{d\sigma(\hat{y} - \text{polarized})}_{QED}, \quad \mathcal{R}_{QED - NCP} = \frac{d\sigma(\hat{x} - \text{polarized})}{d\sigma(\hat{y} - \text{polarized})}_{QED - NCP},$$

and the normalized difference between the QED prediction and the QED-NCP prediction of the ratio:

$$\frac{\mathcal{R}_{QED} - \mathcal{R}_{QED - NCP}}{\mathcal{R}_{QED}}.$$

The normalized difference shown in Fig. 8(b) suggests that a precise measurement of the backward Compton scattering in Spring-8 with initial photon polarization perpendicular to and parallel the magnetic field is still worth to distinguish the prediction of QED-NCP from that of QED without NCP.

![Graph](image)

(a) QED prediction of the energy dependence of the differential cross section with $\alpha = \frac{7}{30}\pi$.

(b) Energy dependence of the normalized difference of ratio with $f = 2 \times 10^{-4}$.

FIG. 8: Suppose the initial photon in Fig. 4 is $\alpha$-polarized.

For both cases, it is practicable to reveal the QED-NCP effects by means of a precise measurement of backward Compton scattering in strong uniform magnetic field. It should be interesting and remarkable.

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