

Strong-field physics as a new probe of early-time dynamics in heavy-ion collisions

Kazunori Itakura

Theory Center, IPNS, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

E-mail: kazunori.itakura@kek.jp

Abstract. In high-energy heavy-ion collisions, there appear two kinds of extremely strong fields: Ordinary electromagnetic fields and non-Abelian color Yang-Mills fields called a glasma. I explain how they are created in collisions, how strong they are, and how important they are in understanding early-time “pre-equilibrium” evolution of collision events. As one of the typical strong-field “nonlinear QED” phenomena, I discuss possible relevance of the “vacuum birefringence” of a photon in probing the very early-time dynamics of heavy-ion collisions.

1. Introduction: What is strong-field physics?

One of the most difficult unsolved problems in high-energy heavy-ion collisions (HICs) is to clarify the mechanism that drives created matter into a thermalized QGP. In this talk, I emphasize that strong-field physics provides a new tool to investigate the early-time dynamics of HICs. By “strong-field physics”, I mean characteristic phenomena that occur only when the (external) gauge fields are strong. For example, consider an electron propagator in a strong magnetic field (Fig. 1, left). Each insertion of an external magnetic field gives a factor eB/m_e^2 and thus such tree diagrams are enhanced when the magnetic field is stronger than the “critical magnetic field”, $B_c \equiv m_e^2/e$, and all order summation of such diagrams yields results which are non-perturbative with respect to the coupling, and nonlinear with respect to the magnetic field B . Figure 2 shows typical strong-field phenomena that occur with such ‘dressed’ electrons under strong magnetic fields: (a) vacuum polarization which induces birefringence phenomena of a photon, and (b) photon splitting which is prohibited in the ordinary vacuum. Notice that the corresponding electric field $E_c = m_e^2/e$ is the “Schwinger field” beyond which creation of e^+e^- pairs from the vacuum becomes possible. All these kinds of phenomena are called “nonlinear QED effect” (for more details in relation to heavy-ion physics, see Ref. [1]).

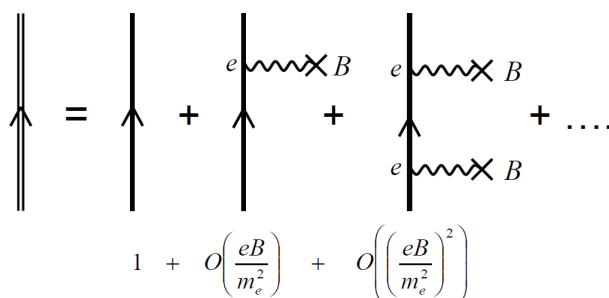


Figure 1. Electron propagator in an external magnetic field.

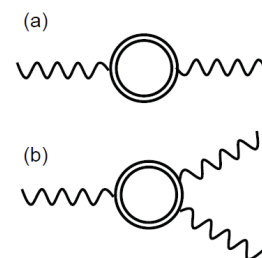


Figure 2. (a) vacuum polarization
(b) photon splitting

Strength	Realized as	Strength	Realized as
8.3×10^4	supercond. magnets in LHC	$0.5 (= m_e)$	critical field for electrons (EM)
4.5×10^5	strongest steady field	$\sim 2 - 3$	magnetars (EM)
$\sim 10^{12}$	neutron stars	$\sim 10^2 (\sim m_\pi)$	noncentral HIC at RHIC (EM)
4×10^{13}	critical field for electrons	$\sim 4 \times 10^2$	noncentral HIC at LHC (EM)
$\sim 10^{15}$	magnetars	$\sim 10^3 (\sim Q_s)$	gluon fields at RHIC (YM)
$\sim 10^{17}, 10^{18}$	noncentral HIC at RHIC & LHC	$(2 - 3) \times 10^3$	gluon fields at LHC (YM)

Table 1. Comparison of EM and YM fields in various situations in unit of Gauss (left, only ordinary magnetic field B) and MeV (right, \sqrt{eB} for EM fields and \sqrt{gB} for YM fields).

2. Two strong fields in HICs

High-energy HICs create two different kinds of strong fields: Ordinary electromagnetic fields and non-Abelian color Yang-Mills fields called a glasma [3]. Both of them are strongest at the earliest time, but they play different roles. The glasma is a transitional state between the initial condition (color glass condensate) and QGP, and thus we need to understand thermalization as a result of time evolution of the glasma. On the other hand, the electromagnetic fields appear in noncentral collisions, and are absent (or, at most, small with fluctuation included) in central collisions where creation of QGP is easier than in noncentral collisions. Thus, the electromagnetic fields will not play a significant role in thermalization, but characteristic phenomena induced by strong electromagnetic fields can be good probes of the earliest-time matter.

Let us overview how strong they are. Table 1 is a comparison of magnetic fields realized in various situations. It shows several situations in Nature (neutron stars, magnetars), but in fact the magnetic fields created in high-energy HICs are much stronger than any of them including the critical magnetic field for electrons $B_c = m_e^2/e = 4 \times 10^{13}$ Gauss. The maximum strength amounts to $\sim 10^{17}$ Gauss at RHIC and $\sim 10^{18}$ Gauss at LHC, far above the critical value. Since the origin of magnetic fields is fast moving nuclei with electric charges, such strong fields last only for a very short period (see Fig. 3). However, with the strongest “supercritical” magnetic fields, we expect many interesting phenomena related to nonlinear QED to occur.

HICs produce non-Abelian glasma fields, too. Similar to the electromagnetic fields discussed above, the origin of glasma fields is also the colliding nuclei. At high energy, the colliding nucleus is dominated by gluons having very small fractions of momentum. They are successively emitted from valence partons distributing randomly on the transverse disk (Lorentz-contracted nucleus), and are densely populated. Thus they are collectively treated as a field, and its strength is very high. This state is called the color glass condensate (CGC). After the collision, this dense gluons generate a glasma field that is also strong. Reflecting the random structure on the transverse disk in CGC, the glasma has a flux tube structure extending in the beam direction. Thus the problem is to understand time evolution of the glasma with a flux tube structure towards thermalization.

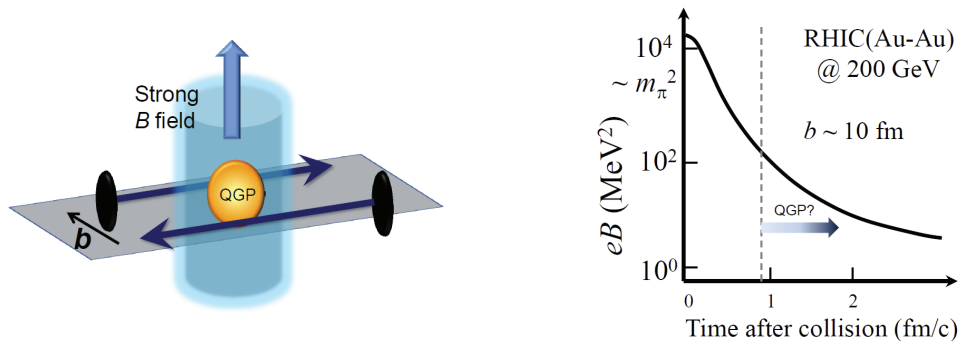


Figure 3. In noncentral HICs, very strong magnetic fields are created perpendicular to the reaction plane. They decay rapidly, but are still strong enough when QGP is formed at $\tau \sim 1$ fm [2].

Since one cannot directly compare the strength of color fields with that of ordinary electromagnetic fields, let us compare them in unit of energy. Right of Table 1 is a comparison of the ordinary and color electromagnetic fields. For the electromagnetic fields we show \sqrt{eB} in unit of MeV, and for color electromagnetic fields \sqrt{gB} in the same energy scale where g is the coupling strength and B is the color magnetic fields. Notice that the critical “color” field in QCD should be determined by quark mass m_q . Still, the strength $\sqrt{gB} \sim Q_s \sim 1$ GeV at RHIC (Q_s is the saturation momentum, a typical momentum of gluons in CGC) is well beyond the critical value $m_q \sim$ a few MeV, suggesting the importance of Schwinger mechanism of $q\bar{q}$ pair production. Moreover, gluon pair production is also possible from color “electric” glasma since gluons are massless. Recently, it is gradually being recognized that unstable dynamics of the glasma is important for, at least, isotropization of the system, which should be the first step towards thermalization. In addition to the Schwinger mechanism mentioned above, the “magnetic” glasma fields are unstable against small fluctuation perpendicular to the direction of the glasma color field [4, 5]. This is a revival of the famous Nielsen-Olesen instability [6] which was originally discussed in context of finding a true vacuum in Yang-Mills theory. Most recently, it has also been found that in the presence of both the color magnetic and electric fields, anomalously large number of gluons will be produced via the Schwinger mechanism enhanced by the Nielsen-Olesen instability [7].

3. Vacuum birefringence of a photon and possible effects in HICs

Photons are emitted at all stages of HICs. Direct photons are created in the initial hard collisions, thermal photons are from QGP, and decay photons are from decays of (mainly) pions. In addition to these well-known photon sources, in the presence of strong magnetic fields, there will be synchrotron radiation from quarks [8]. Since photons do not directly interact via strong interaction, they escape from the collision area, and carry the information of initial stages of HIC events. However, when extracting such information, we have to be careful about the nonlinear QED effects on photons. In particular, the initial direct photons and thermal photons from the earliest time QGP will be affected by the magnetic field through the vacuum birefringence.

In an ordinary vacuum, the one-loop self-energy diagram of a photon propagator, or the polarization tensor $\Pi^{\mu\nu}(q)$, does not change the speed of light. However, in the presence of a strong magnetic field that selects a specific direction in space, the tensor $\Pi^{\mu\nu}(q, B)$ acquires additional terms that depend on B (see Fig. 2(a)). Consequently, a photon can have, in general, refractive indices different from unity just as if the vacuum behaves as a medium. The refractive indices of two physical propagating modes are not necessarily the same, thus this is called “birefringence”. More specifically, the polarization tensor of a photon at one-loop level is given by

$$i\Pi^{\mu\nu}(q, B) = (-ie)^2(-1) \int \frac{d^4p}{(2\pi)^4} \text{Tr} [\gamma^\mu G(p, A) \gamma^\nu G(p+q, A)] , \quad (1)$$

where $G(p, A)$ is the electron propagator in a magnetic field, $iG^{-1}(p, A) = \not{p} - e\not{A} - m_e$. Note that this propagator incorporates all-order contributions with respect to the external magnetic field. We assume that the magnetic field is oriented to the third direction in spatial coordinates. With the special direction specified by the magnetic field, the Lorentz structure of the polarization tensor $\Pi^{\mu\nu}$ is now modified as

$$\Pi^{\mu\nu}(q, B) = -\chi_0 [q^2 \eta^{\mu\nu} - q^\mu q^\nu] - \chi_1 [q_\parallel^2 \eta_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu] - \chi_2 [q_\perp^2 \eta_\perp^{\mu\nu} - q_\perp^\mu q_\perp^\nu] , \quad (2)$$

where the metric $\eta^{\mu\nu} = \text{diag}(1, -1, -1, -1)$ and the photon momentum $q^\mu = (q^0, q_\perp, 0, q^3)$ are decomposed into two parts (parallel and perpendicular to the magnetic field); $\eta_\parallel^{\mu\nu} = \text{diag}(1, 0, 0, -1)$, $\eta_\perp^{\mu\nu} = \text{diag}(0, -1, -1, 0)$, and $q_\parallel^\mu = (q^0, 0, 0, q^3)$, $q_\perp^\mu = (0, q_\perp, 0, 0)$, and χ_i

($i = 0, 1, 2$) are scalar functions of q_{\parallel}^2 , q_{\perp}^2 and B . Without the magnetic field, we see that both χ_1 and χ_2 vanish, and that the last two terms are absent in a vacuum. With this polarization tensor, the Maxwell equation gets modified as $[q^2\eta^{\mu\nu} - q^{\mu}q^{\nu} - \Pi^{\mu\nu}(q, B)]A_{\nu}(q) = 0$. By solving this equation, one obtains dispersion relations for two physical modes. One finds that, when χ_1 and/or χ_2 are nonzero, these two are distinct from each other differently from those in a vacuum, $\omega^2 = \mathbf{q}^2$. Defining the refractive index n by

$$n^2 = \frac{|\mathbf{q}|^2}{\omega^2}, \quad (3)$$

one obtains two different refractive indices

$$n_1^2 = \frac{1 + \chi_0 + \chi_1}{1 + \chi_0 + \chi_1 \cos^2 \theta}, \quad n_2^2 = \frac{1 + \chi_0}{1 + \chi_0 + \chi_2 \sin^2 \theta}, \quad (4)$$

where $q^{\mu} = (\omega, q_{\perp}, 0, q_{\parallel}) = (\omega, |\mathbf{q}| \sin \theta, 0, |\mathbf{q}| \cos \theta)$. Of course, when χ_1 and χ_2 are vanishing, both n_1 and n_2 reduce to unity. It should be noticed that the refractive indices n_i depend on the angle θ , and when $\theta = 0$ (a photon propagates in parallel to the magnetic field), both n_1 and n_2 are 1. Most recently, one-loop contribution to the vacuum polarization tensor has been analytically computed [9], and one can explicitly compute the refractive indices in strong magnetic fields.

As mentioned above, there is an azimuthal angle θ dependence. When a photon propagates in parallel to the magnetic field, or perpendicularly to the reaction plane in noncentral HIC, there is no effect. On the other hand, if a photon propagates perpendicularly to the magnetic field, or in the reaction plane, then modification of refractive indices is very large. If the photon energy is large enough, it can even decay into an e^-e^+ pair. Therefore, if the photons are emitted isotropically, magnetic fields will add azimuthal dependence (leading to negative v_2).¹ Besides, since the magnetic field should have nontrivial profile, if trajectories of two photons are different, the effects of birefringence will be different. Thus, we expect distortion of the HBT image in strong magnetic fields. This was studied in a very simple model [10], and it was found that the strong magnetic field works like a distorted lens. From these nonlinear QED effects, we are, in principle, able to extract information of the early-time HIC events. I hope future experiments can resolve these physics and contribute to disentangle the early-time dynamics of HIC events.

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¹ However, we need to also consider synchrotron radiation from quarks which will contribute positively to v_2 . Synchrotron radiation is emitted along the circular trajectory of the quark.