Potential analysis in holographic Schwinger effect in Einstein–Maxwell–Gauss–Bonnet gravity

Zi-qiang Zhang

School of Mathematics and Physics, China University of Geosciences, Wuhan 430074, China

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Abstract

We perform the potential analysis in holographic Schwinger effect in Einstein–Maxwell–Gauss–Bonnet (EMGB) gravity. The static potential is evaluated by the classical string action attaching on a probe D3-brane sitting at an intermediate position in the bulk anti-de Sitter (AdS) space. It is shown that chemical potential $\mu$ and positive Gauss–Bonnet (GB) coefficient $\lambda_{GB}$ enhance the production rate while negative $\lambda_{GB}$ reduce it. Also, we determine the critical electric field by Dirac–Born–Infeld (DBI) action.

1. Introduction

Schwinger effect is an intriguing phenomenon in quantum electrodynamics (QED): virtual electron-position pairs can be materialized and become real particles under a strong electric-field. The production rate $\Gamma$ was evaluated by Schwinger for the case of weak-coupling and weak-field in 1951

$$\Gamma \sim \exp\left(-\frac{\pi m^2}{eE}\right),$$

where $E$ denotes the external electric-field, $m$, $e$ are the mass and charge of the created particles, respectively. In this case, there is no critical field trivially. Thirty years later, the investigation of $\Gamma$ has been generalized to the case of arbitrary-coupling and weak-field [2]

E-mail address: zhangzq@cug.edu.cn.

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\[ \Gamma \sim \exp \left( \frac{-\pi m^2}{eE} + \frac{e^2}{4} \right), \quad (2) \]

in this case, the exponential suppression vanishes when \( E \) reaches \( eE = (4\pi/e^2)m^2 \approx 137m^2 \). But the critical value \( E_c \) is far beyond the weak-field condition \( eE \ll m^2 \). Hence, it seems that one could not find out the critical field under the weak-field condition. Or more immediately, one doesn’t know whether the catastrophic decay would really occur or not.

Interestingly, there exists a critical value for the electric field, \( E_c \approx \frac{1}{2\pi a^2} \), in string theory, and at \( E_c \) the catastrophic vacuum decay may occur [3,4]. It is known that a string theory on an AdS space can dual to a conformal field theory (CFT) in the physical space–time through the AdS/CFT correspondence [5–7]. Thus, one would be able to study the Schwinger effect from holography. On the other hand, the Schwinger effect is not confined to QED but usual for quantum field theories (QFTs) coupled to an U(1) gauge field. Several years ago, Semenoff and Zarembo remarked [8] that a \( \mathcal{N} = 4 \) SYM theory system coupled with an U(1) gauge field can be realized by breaking the gauge group from \( SU(N + 1) \) to \( SU(N) \times U(1) \) via the Higgs mechanism. Utilizing this approach, the production rate and the critical electric field, at large \( N \) and large ‘t Hooft coupling \( \lambda \equiv N\alpha_s^2 M^2 \), are obtained as

\[ \Gamma \sim \exp \left[ -\frac{\sqrt{\lambda}}{2} \left( \sqrt{\frac{E_c}{E}} - \sqrt{\frac{E}{E_c}} \right)^2 \right], \quad E_c = \frac{2\pi m^2}{\sqrt{\lambda}}, \quad (3) \]

remarkably, the resulting critical field completely agrees with the DBI result. Later, this idea has been generalized to various cases. For example, the Schwinger effect in confining backgrounds is studied in [9]. The universal aspects of this effect are discussed in [10]. The potential analysis for this effect is analyzed in [11]. The Schwinger effect and negative differential conductivity are addressed in [12]. Other important results can be found, for instance, in [13–18]. In addition, the holographic Schwinger effect has been studied from the imaginary part of a probe brane action, investigations in this direction see [19–22].

Here we give such analysis in the bulk with curvature corrections and a gauge potential. From the point of view of the AdS/CFT, curvature corrections correspond to \( 1/\lambda \) or \( 1/N \) corrections to the boundary theory [23,24] and a gauge potential corresponds to a chemical potential in the boundary field theory. To our knowledge, previous works only consider single effect (on the holographic Schwinger effect) but ignores another, e.g. the chemical potential effect [16] and the GB corrections [17]. In this work we focus on the combination of these two effects. Specifically, we would like to explore whether the chemical potential and GB coefficient have the same effect on the Schwinger effect. If not, this model will provide theoretically a wider range of this quantity. Also, this work could be regarded as the generalization of [11] to the case with chemical potential and GB corrections.

Our main results are summarized as follows:

1. At fixed \( \lambda_{GB} \), increasing \( \mu \) leads to decreasing the potential barrier, which means the presence of chemical potential enhances the Schwinger effect.
2. At fixed \( \mu \), increasing \( \lambda_{GB} \) leads to decreasing the potential barrier, implying positive \( \lambda_{GB} \) enhances the Schwinger effect while negative \( \lambda_{GB} \) reduces it.

The organization of this paper is as follows. In section 2, we briefly review the background of the EMGB gravity. In section 3, we perform the potential analysis for the Schwinger effect and calculate the critical electric field by DBI action. Also, we discuss how chemical potential and GB coefficient affect the production rate, respectively. The last part is devoted to conclusion and discussion.
2. Background geometry

The action in \( D (D \geq 5) \) dimensional Einstein–Maxwell gravity with Gauss–Bonnet term is given by [25]

\[
I = \frac{1}{2\kappa^2} \int d^Dx \sqrt{-g} \left( R - 2\Lambda - \frac{4\pi G_D}{g^2} F_{\mu\nu}F^{\mu\nu} + \lambda_{GB} L_{GB} \right),
\]

(4)

with

\[
2\kappa^2 = 16\pi G_D, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad L_{GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma},
\]

(5)

where \( G_D \) is the D-dimensional gravitational constant, \( g^2 \) refers to D-dimensional gauge coupling constant. \( R \) denotes the Ricci scalar, \( \lambda_{GB} \) stands for the GB coefficient. \( \Lambda \) represents the negative cosmological constant and related to AdS radius by \( L = \sqrt{-6/\Lambda} \).

For action (4), the corresponding Einstein equation is

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G_D}{g^2} \left( F_{\mu\rho} F_{\nu\sigma} g^{\rho\sigma} - \frac{1}{4} g_{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} \right) + T_{\mu\nu}^{\text{eff}},
\]

(6)

with

\[
T_{\mu\nu}^{\text{eff}} = \lambda_{GB} \left[ \frac{1}{2} g_{\mu\nu} \left( R^2 - 4R_{\alpha\beta} R^{\alpha\beta} + R_{\alpha\beta\rho\sigma} R^{\alpha\beta\rho\sigma} \right) - 2RR_{\mu\nu} + 4R_{\mu\rho} R_{\nu}^{\rho} \\
+ 4R_{\rho\sigma} R_{\mu\nu} R^{\rho\sigma} - 2R_{\mu\rho\gamma} R_{\nu}^\rho R_{\rho}^\gamma \right].
\]

(7)

For equation (7), many exact solutions have been studied, see [26–32]. In this work, we are interested in 5-dimensional case \((D = 5)\). The corresponding metric is

\[
ds^2 = -H(r)N^2 dt^2 + \frac{r^2}{L^2} d\bar{x}^2 + \frac{dr^2}{H(r)},
\]

(8)

with

\[
H(r) = \frac{r^2}{4\lambda_{GB}} \left[ 1 - \sqrt{1 - \frac{8\lambda_{GB}}{L^2} \left( 1 - (q + 1) \frac{r_h^4}{r^4} + q \frac{r_h^6}{r^6} \right)} \right], \quad q = \frac{L^2 \kappa^2}{6g^2} Q^2,
\]

(9)

where \( \bar{x} = x_1, x_2, x_3 \) are the boundary coordinates. \( r \) is the radial coordinate describing the 5th dimension. \( Q \) is the black hole charge. \( r_h \) represents the event horizon, defined by the largest root of the equation \( H(r_h) = 0 \). \( N^2 \) refers to a constant which specifies the speed of light of the boundary gauge theory and can be fixed by requiring that the geometry of the spacetime should asymptotically approach to the conformally flat metric as \( r \to \infty \),

\[
N^2 = \frac{1}{2} \left( 1 + \sqrt{1 - 8\lambda_{GB}/L^2} \right),
\]

(10)

where \( \lambda_{GB} \) is constrained in the range [33–37]

\[-\frac{7}{36} \leq \lambda_{GB} \leq \frac{9}{100},
\]

(11)

by considering the causality of dual field theory on the boundary and preserving the positivity of the energy flux in CFT analysis.
Also, the \( U(1) \) gauge potential is given by
\[
A_t = \mu \left( 1 - \frac{r_h^2}{r^2} \right),
\]
(12)
where \( \mu \) is the chemical potential and related to \( Q \) by \( \mu = \frac{Qr_h}{2} \).

The Hawking temperature is
\[
T = \frac{N r_h}{2\pi L^2} (2 - q),
\]
(13)
where \( T \) is identified with the temperature of the CFT on the AdS boundary.

3. Potential analysis in Schwinger effect

Let us perform the potential analysis for the background metric (8). The Nambu–Goto action is
\[
S = T_F \int d\tau d\sigma \mathcal{L} = T_F \int d\tau d\sigma \sqrt{g},
\]
(14)
with \( T_F = \frac{1}{\pi \alpha'} \) the string tension, where \( \alpha' \) is related to \( \lambda \) by \( \frac{\lambda}{\alpha'} = \sqrt{\lambda} \). \( g \) represents the determinant of the induced metric with
\[
g_{\alpha\beta} = g_{\mu\nu} \frac{\partial X^\mu}{\partial \sigma^\alpha} \frac{\partial X^\nu}{\partial \sigma^\beta},
\]
(15)
where \( g_{\mu\nu} \) and \( X^\mu \) are the metric and target space coordinates, respectively.

After the gauge fixing
\[
t = \tau, \quad x_1 = \sigma, \quad x_2 = 0, \quad x_3 = 0, \quad r = r(\sigma),
\]
(16)
the induced metric becomes
\[
g_{00} = H(r)N^2, \quad g_{01} = g_{10} = 0, \quad g_{11} = \frac{r^2}{L^2} + \frac{1}{H(r)} \left( \frac{dr}{d\sigma} \right)^2,
\]
(17)
which yields
\[
\mathcal{L} = \sqrt{A(r) + B(r) \left( \frac{dr}{d\sigma} \right)^2},
\]
(18)
with
\[
A(r) = \frac{H(r)N^2 r^2}{L^2}, \quad B(r) = N^2.
\]
(19)
Since \( \mathcal{L} \) does not depend on \( \sigma \) explicitly, the corresponding Hamiltonian is a constant
\[
\mathcal{H} = \mathcal{L} = \frac{\partial \mathcal{L}}{\partial \dot{r}} \dot{r} = \text{Constant},
\]
(20)
Imposing the boundary condition at \( \sigma = 0 \),
\[
\dot{r} = 0, \quad r = r_c \quad (r_h < r_c < r_0),
\]
(21)
where the probe D3-brane is put at an intermediate position \( (r = r_0) \) between the horizon and the boundary. It was argued [8] that such manipulation can yield a finite mass.
To proceed, one gets

$$\frac{dr}{d\sigma} = \sqrt{\frac{A^2(r) - A(r)A(r_c)}{A(r_c)B(r)}}. \quad (22)$$

with

$$A(r_c) = \frac{H(r_c)N^2r_c^2}{L^2}, \quad H(r_c) = \frac{r_c^2}{4\lambda GB}\left[1 - \sqrt{1 - \frac{8\lambda GB}{L^2}\left(1 - (q + 1) \frac{r_h^4}{r_c^4} + q \frac{r_h^6}{r_c^6}\right)}\right]. \quad (23)$$

By integrating (22), the separate length of the test particles is expressed as

$$x = 2L \frac{r_0a}{1} \int dy \sqrt{\frac{A(y)B(y)}{A^2(y) - A(y)A(y_c)}}, \quad (24)$$

with

$$A(y) = H(y)N^2y^2, \quad A(y_c) = H(y_c)N^2, \quad B(y) = N^2, \quad \quad (25)$$

$$H(y) = \frac{y^2}{4\lambda GB}\left[1 - \sqrt{1 - \frac{8\lambda GB}{L^2}\left(1 - (q + 1) \frac{b^4}{(ay)^4} + q \frac{b^6}{(ay)^6}\right)}\right], \quad (26)$$

$$H(y_c) = \frac{1}{4\lambda GB}\left[1 - \sqrt{1 - \frac{8\lambda GB}{L^2}\left(1 - (q + 1) \frac{b^4}{a^4} + q \frac{b^6}{a^6}\right)}\right], \quad (27)$$

where we have defined the following dimensionless parameters:

$$y \equiv \frac{y}{r_c}, \quad a \equiv \frac{r_c}{r_0}, \quad b \equiv \frac{r_h}{r_0}. \quad (28)$$

On the other hand, from (14), (18) and (22), the sum of Coulomb potential and static energy is obtained as

$$V_{C P + E} = 2TF r_0 a \int \frac{1}{1} dy \sqrt{\frac{A(y)B(y)}{A^2(y) - A(y)A(y_c)}}, \quad (29)$$

The next step is to calculate the critical field. The DBI action is

$$S_{DBI} = -T_D^3 \int d^4x \sqrt{-\det(G_{\mu\nu} + F_{\mu\nu})}, \quad (30)$$

with

$$T_D^3 = \frac{1}{g_s(2\pi)^3\alpha'^2}, \quad F_{\mu\nu} = 2\pi \alpha' F_{\mu\nu}, \quad (31)$$

where $T_D^3$ is the D3-brane tension.

In terms of (8), the induced metric $G_{\mu\nu}$ reads

$$G_{00} = -H(r)N^2, \quad G_{11} = G_{22} = G_{33} = \frac{r^2}{L^2}. \quad (32)$$
Supposing that the electric field is turned on along the $x_1$-direction (implying $E_2 = E_3 = 0$), one has

\[
G_{\mu\nu} + F_{\mu\nu} = \begin{pmatrix} -H(r)N^2 & 2\pi\alpha'E & 0 & 0 \\ -2\pi\alpha'E & \frac{r^2}{L^2} & 0 & 0 \\ 0 & 0 & \frac{r^2}{L^2} & 0 \\ 0 & 0 & 0 & \frac{r^2}{L^2} \end{pmatrix},
\]

which yields

\[
det(G_{\mu\nu} + F_{\mu\nu}) = \frac{r^4}{L^4} \left[ (2\pi\alpha')^2 E^2 - \frac{r^2}{L^2} H(r)N^2 \right].
\]

Plugging (34) into (30) and making the D3-brane located at $r = r_0$, one gets

\[
S_{DBI} = -T_D \frac{r_0^2}{L^2} \int d^4x \sqrt{r_0^2 \frac{r^2}{L^2} H(r_0)N^2 - (2\pi\alpha')^2 E^2},
\]

with

\[
H(r_0) = \frac{r_0^2}{4\lambda_{GB}} \left[ 1 - \sqrt{1 - \frac{8\lambda_{GB}}{L^2} \left( 1 - (q + 1)b^4 + q\beta b^6 \right)} \right].
\]

To avoid (35) being ill-defined, one needs

\[
\frac{r_0^2}{L^2} H(r_0)N^2 - (2\pi\alpha')^2 E^2 \geq 0,
\]

which yields

\[
E \leq T_F \frac{r_0}{L} \sqrt{H(r_0)N^2}.
\]

Consequently, the critical field is

\[
E_c = T_F \frac{r_0}{L} \sqrt{H(r_0)N^2},
\]

one can see that $E_c$ depends on the temperature, chemical potential as well as the GB coefficient.

Next we compute the total potential $V_{\text{tot}}(x)$. For the sake of notation simplicity, we use a dimensionless parameter $\alpha$ like

\[
\alpha = \frac{E}{E_c}.
\]

Together with (24), (29) and (40), one gets

\[
V_{\text{tot}}(x) = V_{CP} + E \chi
\]

\[
= 2T_F r_0 \alpha \int_1^{1/\alpha} dy \sqrt{A(y)B(y)} \sqrt{A(y) - A(\chi_c)}
\]

\[
- \frac{2T_F\alpha}{\alpha} \sqrt{H(r_0)N^2} \int_1^{1/\alpha} dy \sqrt{A(\chi_c)B(y)} \sqrt{A(\chi_c) - A(y)A(\chi_c)}.
\]

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Fig. 1. $V_{\text{eff}}$ versus $x$ with $V_{\text{eff}} = 2m - Ex - \frac{q}{2}$, where $\alpha$ is a fine-structure constant.

Fig. 2. $V_{\text{tot}}(x)$ against $x$ with $\mu = 0.2$, $\lambda_{\text{GB}} = 0.01$. In the plots from top to bottom $\alpha = 0.8, 0.9, 1.0, 1.1$, respectively.

Notice that by taking $H(r) = \frac{r^2}{L^2}(1 - \frac{r_0^4}{r^4})$ and $N^2 = 1$ in (41), one regains the result of $N = 4$ case [11]. Moreover, if one neglects the effects of GB corrections in (41), the result of [16] is recovered. Also, by setting $\mu = 0$ in (41), the result of [17] is reproduced.

Before going on, we recall the potential analysis in Schwinger effect [11]. As shown in Fig. 1, there are three cases for the potential. When $E < E_c$, the potential barrier is present and the pair production can be described as a tunneling process. As $E$ increases, the potential barrier decreases gradually and vanishes at $E = E_c$. When $E > E_c$, the vacuum is catastrophically unstable.

Next, we determine the values of some parameters. First, we set $\kappa^2 = g^2 = L = T_F = r_0 = 1$ and $b = 0.5$, similar to [11,27]. Second, to ensure the temperature of (13) to be positive, we take $q < 2$, which gives $\mu < \sqrt{3}$. Also, we will not discuss the points of $\lambda_{\text{GB}} = 0$, since $\lambda_{\text{GB}}$ appears in the denominator.

Let’s discuss results. First, we analyze the shapes of the potential for a general case. To this end, we plot $V_{\text{tot}}(x)$ against $x$ with $\mu = 0.2$, $\lambda_{\text{GB}} = 0.01$ in Fig. 2. Other cases with different $\mu$ and $\lambda_{\text{GB}}$ (within the allowable range) have similar picture. From the figures, one can see that
there exists a critical electric field at $\alpha = 1$ ($E = E_c$), and for $E < E_c$, the potential barrier is present, so the Schwinger effect can occur as tunneling process, in agreement with [11].

Second, we study the effect of $\mu$ on the Schwinger effect. In Fig. 3, we plot $V_{tot}(x)$ as a function of $x$ with fixed $\lambda_{GB}$ for different values of $\mu$. One sees that at fixed $\lambda_{GB}$, the height and width of the potential barrier both decrease as $\mu$ increases. As we know, the higher the potential barrier the harder the produced pair escape to infinity. Thus, one concludes that the inclusion of chemical potential increases the Schwinger effect. On the other hand, we plot $\Gamma(E)$ in Eq. (3) as a function of $E$ for this case in Fig. 4. One can get the same result: increasing $\mu$ increases the production rate, consistent the findings of [16].

Next, we analyze how $\lambda_{GB}$ affects the Schwinger effect. In Fig. 5, we plot $V_{tot}(x)$ versus $x$ with fixed $\mu$ for three different values of $\lambda_{GB}$. From the figures, one clearly sees that increasing $\lambda_{GB}$ leads to decreasing the potential barrier thus enhancing the Schwinger effect. However, it should be noticed that $\lambda_{GB}$ can be positive or negative (see Eq. (11)), therefore, the inclusion of $\lambda_{GB}$ may increase or decrease the Schwinger effect, similarly to what occurred in [17]. Also, one can get the same results from Fig. 6 which shows $\Gamma(E)$ against $E$.

On the other hand, we would like to discuss the effects of $\mu$ and $\lambda_{GB}$ on $E_c$. To do that, in Fig. 7 we plot $E_c$ versus $\mu$ for different values of $\lambda_{GB}$ and $E_c$ versus $\lambda_{GB}$ for different
Fig. 5. $V_{tot}(x)$ versus $x$ with $\alpha = 0.8$ and fixed $\mu$ for different values of $\lambda_{GB}$. In both plots from top to bottom $\lambda_{GB} = -0.19, 0.01, 0.09$, respectively.

Fig. 6. $\Gamma(E)$ versus $E$ with fixed $\mu$ for different values of $\lambda_{GB}$. In both plots from bottom to top $\lambda_{GB} = -0.19, 0.01, 0.09$, respectively.

Fig. 7. Left: $E_c$ versus $\mu$ for different values of $\lambda_{GB}$. Right: $E_c$ versus $\lambda_{GB}$ for different values of $\mu$.

values of $\mu$, respectively. From the figures, one finds that increasing $\mu$ and $\lambda_{GB}$ both reduce $E_c$. Moreover, by comparing with the $N = 4$ SYM case (which corresponds to $E_{c0} \simeq 0.968$ if one uses the parameters considered here), the value of $E_c$ can be larger or smaller than $E_{c0}$, which supports the previous potential analysis.
4. Conclusion and discussion

In this paper, we studied the effects of chemical potential and GB coefficient on the holographic Schwinger effect in Einstein–Maxwell–Gauss–Bonnet gravity. We examined the electrostatic potentials by calculating the Nambu–Goto action of a string attaching the rectangular Wilson loop on a probe D3 brane. Also, we analyzed $E_c$ from DBI action and plotted it as functions of $\mu$ and $\lambda_{GB}$ for various cases. It is found that increasing $\lambda_{GB}$ and $\mu$ both decrease the potential barrier thus increasing the Schwinger effect, which confirms earlier findings. Moreover, we find that with some chosen values of $\mu$ and $\lambda_{GB}$, $\Gamma$ can be larger or smaller than its counterpart of the $\mathcal{N}=4$ SYM case. In other words, this model provides theoretically a wider range of the Schwinger effect.

However, several questions remain. The most pertinent one would be to consider a non-constant electric field, as for a system of de-confined charged particles, there cannot be a constant electric field at finite temperature due to the Debye screening. Moreover, the model considered here has no dynamical breaking of the conformal symmetry, which renders this work not applicable for real-world QCD phenomenology. It would be of great interest to pursue in investigations performed on top of phenomenologically realistic guague/gravity backgrounds. We hope to report our progress in this regard in the near future.

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