

# GUP assisted Hawking radiation of rotating acoustic black holes

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**Abstract** Recent studies (Steinhauer in *Nat. Phys.* 10:864, 2014, *Phys. Rev. D* 92:024043, 2015) provide compelling evidences that Hawking radiation could be experimentally proven by using an analogue black hole. In this paper, taking this situation into account we study the quantum gravitational effects on the Hawking radiation of rotating acoustic black holes. For this purpose, we consider the generalized uncertainty principle (GUP) in the phenomenon of quantum tunneling. We firstly take the modified commutation relations into account to compute the GUP modified Hawking temperature when the massive scalar particles tunnel from this black hole. Then, we find a remarkably instructive expression for the GUP entropy to derive the quantum gravity corrected Hawking temperature of the rotating acoustic black hole.

**Keywords** Rotating acoustic black holes · Hawking radiation · Generalized uncertainty principle · Quantum gravity · Entropy correction

## 1 Introduction

In a landmark agreement of general relativity and quantum field theory (known as quantum gravity theory) Hawking (Hawking 1971, 1974, 1975, 1976) predicted that a black hole (BH) could emit a blackbody like radiation which is the so-called Hawking radiation (HR). In fact, HR asserts

that any (not naked) BH, due to the vacuum fluctuations, can evacuate the quantum particles generated from the virtual particle pairs which obey the annihilation-creation mechanism of the quantum field theory. It is hypothesized that in each HR process, one of these particles which has negative energy falls into the BH to reduce its mass, before being annihilated by its spouse (the one with positive energy). Due to the vacua difference the non-absorbed particle can thus escape to spatial infinity, and it could be detected by an observer as a HR particle. The corresponding temperature of the HR is in striking agreement with the first law of thermodynamics which comprises the entropy of the BH (Bekenstein 1972, 1973, 1974, 1975). Unfortunately, the theoretical computations reveal that with today's technology the HR of a cosmological BH (having mass of a few solar masses or greater) is almost impossible. Because, such BHs have extremely a weak radiation. However, using a different space-time configuration one can get arbitrarily strong HR. In particular, HR around a micro BH can tear it apart relatively quickly (Helfer 2003).

Unruh (1981, 1995) proposed a theoretical method which renders the HR detection possible by stimulating an analogue BH (a quantum fluid originated from Bose–Einstein condensation) in a laboratory environment. His argument was based on the fact that a transition from subsonic flow to supersonic flow is analogous to a BH event horizon. After then, numerous systems (ultracold fermions, electromagnetic waveguides, light in a nonlinear liquid, etc.) have been proposed for the analogue BHs (see Leonhardt 2002; Nambu et al. 2009; Carbonaro 2015; Iorio 2015; Richartz et al. 2015 and references therein). For example, Corley and Jacobson (1999) came up with a new idea for the possible detection of the HR, which is about condensed matter BH laser. According to their Gedanken experiment, when a BH possesses two horizons, HR reflects between those horizons and by this

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way, in each round trip, an amplified radiation could disperse around the BH: natural increase in the probability of HR detection.

Since Unruh’s seminal papers (Schützhold and Unruh 2002), it has been understood that in the theory of supersonic acoustic flows the BH physics could be mimicked. The obtained acoustic black holes (ABHs) govern the propagation of sound, which depends algebraically on the flow velocity and density (Anacleto et al. 2010, 2011). Recently remarkable progress has been achieved in modeling the HR within the laboratory (Steinhauer 2014, 2015). So, these developments will not only help the physicists to understand the most profound insights about the quantum gravity, but they increase the popularity of the ABHs in the literature, as well. The HR of the ABH was firstly studied by Li-Chun et al. (2011) who employed two different methods in their computations: the reduced global embedding approach and analytical continuation method of wave function across the acoustic horizon. The main aim of this paper is to continue the spirit of Li-Chun et al. (2011) and give supplementary quantum gravity effects on the HR of the ABH by focusing on the GUP (Chen et al. 2014a; Tawfik and Diab 2014; Tawfik and Dahab 2015).

The remainder of the paper is organized as follows. In Sect. 2, we begin with the spacetime metric for a rotating ABH and discuss some of its basic features. We also show that the associated spacetime metric can be obtained in a static metric structure by performing a simple dragging coordinate transformation. In Sect. 3, we study how a massive chargeless scalar field propagates under the effect of GUP in the background of the ABH. Writing out the associated Klein–Gordon equation (KGE) with GUP, we show that KGE (within the framework of the Hamilton–Jacobi (HJ) method, Vanzo et al. 2011) completely separates with a suitable ansatz and yields GUP corrected Hawking temperature. Section 4 is devoted to derivation of the quantum gravity corrected (QGC) entropy, which we call it simply GUP entropy ( $S_{GUP}$ ). In Sect. 5, we explore the quantum gravity effects on the HR of ABH arising from that of  $S_{GUP}$ . To this end, we perform the quantum tunneling computations prescribed by Parikh and Wilczek (2000). The paper ends with Conclusion in Sect. 6.

## 2 Rotating ABH

The spacetime of the rotating ABH was introduced in Anacleto et al. (2010, 2011). Its line-element reads

$$ds^2 = -F dt^2 + \frac{1}{G} dr^2 - H d\phi dt + K d\phi^2, \tag{1}$$

where the metric functions are given by

$$F = \frac{1}{\lambda_+} \left( 1 - \frac{\lambda_-(A^2 + B^2)}{c^2 r^2} \right), \tag{2}$$

$$G = \frac{\lambda_-}{\lambda_+} \left( 1 - \frac{\lambda_- A^2}{c^2 r^2} \right), \tag{3}$$

$$H = \frac{2B}{c}, \tag{4}$$

$$K = \frac{\lambda_+ r^2}{\lambda_-}. \tag{5}$$

Here  $A, B$  and  $\beta$  are the real constants.  $\lambda_{\pm} = 1 \pm \beta$  and  $c = \sqrt{\frac{dh}{d\rho}}$  denotes the speed of sound. Throughout the paper, without loss of generality, we assume that the constant  $A$  has a positive definite value. The event horizon ( $r_h$ ) of the rotating ABH is conditional on  $g^{rr}(r_h) = G(r_h) = 0$ . So that one gets

$$r_h = \frac{\sqrt{\lambda_-} A}{c}. \tag{6}$$

On the other hand, the condition  $g_{tt}(r_e) = 0$  gives the radius of the ergosphere as follows

$$r_e = \frac{\sqrt{\lambda_-} \sqrt{A^2 + B^2}}{c}. \tag{7}$$

Here we are interested in the frame-dragging effect (a BH drags spacetime with it as it rotates) which is often termed dragging of inertial frames. This effect produces a detectable gyroscopic precession called the Lense–Thirring effect (Bardeen and Petterson 1975). When we use the dragging coordinate transformation (Chen et al. 2014b)  $d\phi = d\varphi - \Omega dt$ , where  $\Omega = \frac{H}{2K}$ , metric (1) becomes

$$ds^2 = -Z dt^2 + \frac{1}{G} dr^2 + K d\varphi^2, \tag{8}$$

where

$$Z = \frac{4KF + H^2}{4K} = \frac{c^2 r^2 - A^2 \lambda_-}{c^2 r^2 \lambda_+}. \tag{9}$$

Hereby, the Hawking temperature of the rotating ABH can be computed (Wald 1984; Li-Chun et al. 2011) as

$$T_H = \frac{1}{4\pi} \sqrt{\frac{G}{Z}} \frac{dZ}{dr} \Big|_{r=r_h} = \frac{\sqrt{\lambda_-}}{4\pi} \frac{dZ}{dr} \Big|_{r=r_h} = \frac{c}{2\pi \lambda_+ A}. \tag{10}$$

## 3 Effect of GUP on quantum tunneling of scalar particles

Employing the modified commutation relations (Kempf et al. 1995), it is shown in Chen et al. (2014a), Chen (2014), Övgün (2016), Wang et al. (2016) that the KGE with GUP for a scalar field  $\Psi$  takes the following form

$$-(i\hbar)^2 \partial^t \partial_t \Psi = [(i\hbar)^2 \partial^i \partial_i + m_p^2] \times [1 - 2\alpha_{GUP}((i\hbar)^2 \partial^i \partial_i + m_p^2)]\Psi, \tag{11}$$

where  $\alpha_{GUP}$  and  $m_p$  are the GUP parameter and mass of the scalar particle (phonon), respectively. The generalized KGE (11) can be solved by using the semiclassical WKB approximation (Övgün 2016). We therefore choose the following ansatz for the scalar field:

$$\Psi(t, r, \phi) = \exp\left(\frac{i}{\hbar} \mathcal{S}(t, r, \phi)\right), \tag{12}$$

where  $\mathcal{S}(t, r, \phi)$  is the classically forbidden action for the tunneling. Inserting the above scalar field  $\Psi$  into Eq. (11) for the background (8), we obtain the following expression (in leading order of  $\hbar$ )

$$\frac{1}{Z}(\partial_t \mathcal{S})^2 = G(\partial_r \mathcal{S})^2 + \frac{1}{K}(\partial_\phi \mathcal{S})^2 + m_p^2 \times \left(1 - 2\alpha_{GUP}G(\partial_r \mathcal{S})^2 - \frac{2\alpha_{GUP}}{K}(\partial_\phi \mathcal{S})^2 - 2\alpha_{GUP}m_p^2\right). \tag{13}$$

Taking the symmetries of the metric (8) into account, one can choose the following HJ ansatz for the action

$$\mathcal{S}(t, r, \phi) = -Et + W(r) + j\phi + C, \tag{14}$$

where  $C$  is a complex constant,  $E$  is the energy, and  $j$  denotes the angular momentum of the particle. Substituting the action (14) into Eq. (13), one gets

$$\frac{1}{Z}E^2 = G(W')^2 + \frac{j^2}{K} + m_p^2 \times \left(1 - 2\alpha_{GUP}G(W')^2 - \frac{2\alpha_{GUP}}{K}j^2 - 2\alpha_{GUP}m_p^2\right). \tag{15}$$

We focus only on the radial trajectories. Therefore, the radial part (by ignoring the higher order terms of  $\alpha_{GUP}$ ) results in the following integral

$$W(r) = \pm \int \frac{1}{\sqrt{\Delta(r)}} \frac{dr}{\sqrt{1 - 2m_p^2\alpha_{GUP}}} \times \sqrt{E^2 - \frac{\Delta(r)}{G} \left(\frac{j^2}{K} + m_p^2\right) (1 - 2m_p^2\alpha_{GUP})}, \tag{16}$$

where

$$\Delta(r) = ZG = \frac{\lambda_- (c^2 r^2 - A^2 \lambda_-)^2}{\lambda_+^2 c^4 r^4}, \tag{17}$$

which vanishes at the event horizon;  $\Delta(r_h) \rightarrow 0$ . In order to work out the integral (16), we first expand the function  $\Delta(r)$  in Taylor’s series near the horizon (Sakalli 2015; Sakalli and Gursel 2016)

$$\Delta(r) \approx \Delta(r_h) + \Delta'(r_h)(r - r_h) + \frac{1}{2}\Delta''(r_h)(r - r_h)^2. \tag{18}$$

Then, we evaluate the integral around the pole located at  $r_h$  by deforming the contour. The result is given by

$$W(r_h) = \pm \frac{i\pi E}{2\sqrt{\lambda_-}} \frac{\lambda_+ r_h}{\sqrt{1 - 2m_p^2\alpha_{GUP}}}. \tag{19}$$

The positive (negative) sign indicates the outgoing (ingoing) phonon. At this point, we should note that the famous factor two problem in the above expression which yields the wrong tunneling rate can be fixed with a procedure described in Akhmedova et al. (2008, 2009). Another way to overcome this problem is to set the probability of ingoing phonons to 100 %. Namely, we have

$$P_- \simeq e^{-2ImW_-} = 1, \tag{20}$$

which leads to

$$ImS_- = ImW_- + ImC = 0. \tag{21}$$

On the other hand, for the outgoing phonon we have

$$ImS_+ = ImW_+ + ImC. \tag{22}$$

From Eq. (19) it is not difficult to see that  $W_+ = -W_-$ . Hence, one reads the tunneling probability of the outgoing phonons as follows

$$P_+ = e^{-2ImS_+} \simeq e^{-4ImW_+}. \tag{23}$$

Finally, using Eqs. (20) and (23) the tunneling rate of phonons becomes

$$\Gamma = \frac{P_+}{P_-} \simeq e^{(-4ImW_+)}. \tag{24}$$

Ultimately, we can find the GUP temperature ( $T_{GUP}$ ) of the ABH by comparing the latter result with the Boltzmann formula  $\Gamma = e^{-\beta E}$ , where  $\beta$  is the inverse temperature (Rovelli 2007). Thus, we have

$$T_{GUP} = \frac{\sqrt{\lambda_-}}{2\pi\lambda_+} \frac{\sqrt{1 - 2m_p^2\alpha_{GUP}}}{r_h} = T_H \sqrt{1 - 2m_p^2\alpha_{GUP}}. \tag{25}$$

As can be seen above, after terminating the GUP parameter i.e.,  $\alpha_{GUP} = 0$ , one can recover the original Hawking temperature (10).

### 4 GUP entropy

In this section, we shall revisit the recent studies (Anacleto et al. 2015a,b) to derive the  $S_{GUP}$  for a BH. In general, the GUP is defined by Ali et al. (2009)

$$\Delta x \Delta p_{GUP} \geq \hbar \left( 1 - \frac{y}{\hbar} \Delta p_{GUP} + \frac{y^2}{\hbar^2} (\Delta p_{GUP})^2 \right), \tag{26}$$

where  $y = \alpha_{GUP} l_p$  in which  $\alpha_{GUP}$  is a dimensionless positive constant and  $l_p = \sqrt{\frac{\hbar G}{c^3}}$  is the Planck length. Equation (26) can be reorganized as

$$\Delta p_{GUP} \geq \frac{\hbar(\Delta x + y)}{2y^2} \left( 1 - \sqrt{1 - \frac{4y^2}{(\Delta x + y)^2}} \right), \tag{27}$$

In fact  $l_p/\Delta x$  is infinitesimally small compared with unity. Without loss our generality, using units  $l_p = G = c = \hbar = k_B = 1$  and in sequel expanding the above equation in Taylor series, we find out

$$\Delta p_{GUP} \geq \frac{1}{\Delta x} \left[ 1 - \frac{\alpha_{GUP}}{2\Delta x} + \frac{\alpha_{GUP}^2}{2(\Delta x)^2} + \dots \right]. \tag{28}$$

As known from introductory quantum mechanics textbooks, in the absence of the GUP effect ( $\alpha_{GUP} = 0$ ) we get the ordinary (Heisenberg) uncertainty principle and its saturated form (Anacleto et al. 2015a,b) as follows

$$\Delta x \Delta p \geq 1, \tag{29}$$

$$\mathcal{E} \Delta x \geq 1, \tag{30}$$

where  $\mathcal{E}$  denotes the energy of a quantum-scale particle. Hence, getting analogy between Eqs. (28) and (29), one can also derive the QGC version of Eq. (30) as Anacleto et al. (2015a)

$$\mathcal{E}_{QGC} \geq \mathcal{E} \left[ 1 - \frac{\alpha_{GUP}}{2(\Delta x)} + \frac{\alpha_{GUP}^2}{2(\Delta x)^2} + \dots \right]. \tag{31}$$

The quantum tunneling rate for a quantum particle with  $\mathcal{E}_{QGC}$  reads Anacleto et al. (2015a)

$$\Gamma \simeq \exp[-2Im\mathcal{I}] = \exp(-\mathcal{E}_{QGC}/T_{QGC}), \tag{32}$$

where  $T_{QGC}$  denotes the QGC temperature. Now, if we compare Eq. (32) with the Boltzmann factor, we obtain

$$T_{QGC} = T_H \left[ 1 - \frac{\alpha_{GUP}}{2(\Delta x)} + \frac{\alpha_{GUP}^2}{2(\Delta x)^2} + \dots \right]^{-1}. \tag{33}$$

Inspiring from the recent studies (Anacleto et al. 2015a,b), we can assign  $\Delta x$  to  $A_h/\pi$ . Thus, employing the first law

of BH thermodynamics, one can derive the GUP entropy as follows

$$\begin{aligned} S_{GUP} &= \int \frac{\kappa dA_h}{8\pi T_{QGC}} = \int \frac{T_H dA_h}{4T_{QGC}} \\ &= \int \frac{dA_h}{4} \left[ 1 - \frac{\pi\alpha_{GUP}}{2A_h} + \frac{\pi^2\alpha_{GUP}^2}{2A_h^2} + \dots \right] \\ &= \frac{A_h}{4} - \frac{\pi\alpha_{GUP}}{8} \ln \frac{A_h}{4} - \frac{\pi^2\alpha_{GUP}^2}{8A_h} + \dots, \end{aligned} \tag{34}$$

where  $A_h$  is the perimeter length of the event horizon and  $\kappa = 2\pi T_H$  is the surface gravity. In Eq. (34), the existence of  $\alpha_{GUP}$  is brought correction terms to the BH entropy. Thus, whenever  $\alpha_{GUP} = 0$  one can reproduce the well-known area law for the BH mechanics:  $S_{GUP}|_{\alpha_{GUP}=0} \rightarrow S = A_h/4$ . Meanwhile, the result obtained in Eq. (34) is in accordance with the earlier works that take account of the influences of the loop quantum gravity and string theory on the quantum corrected entropy (see, for instance, Rovelli 1996; Strominger and Vafa 1996; Solodukhin 1998; Kaul and Majumdar 2000; Arzano et al. 2005 and references therein).

### 5 Quantum gravity corrected Hawking radiation of ABH

The Painlevé–Gullstrand coordinate (PGC) (Painlevé 1921; Gullstrand 1922) system is one of the coordinate transformations in general relativity that defines a spacetime, which is regular at the horizon. The constant time surfaces in the PGCs traverse the event horizon to reach the singularity. In fact, a geometry described by the PGC can be seen as a flow whose current speed is equal to the Newtonian escape velocity at each point. Furthermore, the PGC time is the proper time of an observer who freely falls radially from rest (Hamilton and Lisle 2008; Kanai et al. 2011). In this section, we shall define the PGC form of the ABH and compute its HR via the HJ method (Vanzo et al. 2011). Subsequently, in the framework of the Parikh–Wilczek tunneling method (PWTM) (Parikh and Wilczek 2000), the QGC HR will be studied.

According to Eqs. (3) and (9), one can easily see that

$$G = \lambda_- Z. \tag{35}$$

Therefore metric (8) can be rewritten as

$$ds^2 = -Z dt^2 + \frac{1}{\lambda_- Z} dr^2 + K d\phi^2. \tag{36}$$

After rescaling the radial coordinate to

$$r \rightarrow \sqrt{\lambda_-} \tilde{r}, \tag{37}$$

the latter metric (36) becomes

$$ds^2 = -\tilde{Z}dt^2 + \frac{1}{\tilde{Z}}d\tilde{r}^2 + \tilde{K}d\phi^2, \tag{38}$$

where

$$\tilde{Z} = \frac{c^2\tilde{r}^2 - A^2}{c^2\tilde{r}^2\lambda_+}, \tag{39}$$

$$\tilde{K} = \lambda_+\tilde{r}^2. \tag{40}$$

In metric (38) the event horizon corresponds to

$$\tilde{r}_h = \frac{A}{c}. \tag{41}$$

It is needless to say that the Hawking temperature (10) remains intact in this framework, as it should be. Now, one can pass to the PGCs by applying the following transformation (Mirekhtari and Sakalli 2014) to the metric (38)

$$d\tilde{t} = dt + \frac{\sqrt{1-\tilde{Z}}}{\tilde{Z}}d\tilde{r}, \tag{42}$$

where  $\tilde{t}$  is referred to the PGC time. In fact, as it can be deduced from many introductory textbooks written on the general relativity,  $\tilde{t}$  is equivalent to the proper time in this coordinate system (Robertson and Noonan 1968). Inserting the transformation (42) into metric (38), we get the following line-element

$$ds^2 = -\tilde{Z}d\tilde{t}^2 + 2\sqrt{1-\tilde{Z}}d\tilde{t}d\tilde{r} + d\tilde{r}^2 + \tilde{K}d\phi^2. \tag{43}$$

The relativistic HJ equation (Angheben et al. 2005) of the classical action  $\mathcal{I}$  is given by

$$g^{\mu\nu}\partial_\mu\mathcal{I}\partial_\nu\mathcal{I} + m^2 = 0, \tag{44}$$

where  $m$  is the mass of the phonon. For the metric (43), Eq. (44) results in

$$m^2 - (\partial_{\tilde{t}}\mathcal{I})^2 + 2\sqrt{1-\tilde{Z}}(\partial_{\tilde{t}}\mathcal{I})(\partial_{\tilde{r}}\mathcal{I}) + \tilde{Z}(\partial_{\tilde{r}}\mathcal{I})^2 + \frac{1}{\tilde{K}}(\partial_\phi\mathcal{I})^2 = 0. \tag{45}$$

Letting

$$\mathcal{I} = \mathcal{W}(\tilde{r}) + \mathcal{J}(\phi) - \mathcal{E}\tilde{t}, \tag{46}$$

and in sequel substituting the above ansatz in Eq. (45), we obtain

$$\mathcal{W}_{(\pm)} = \int \frac{\mathcal{E}\sqrt{1-\tilde{Z}} \pm \sqrt{\mathcal{E}^2 - \tilde{Z}(m^2 + \frac{(\partial_\phi\mathcal{J})^2}{\tilde{K}})}}{\tilde{Z}}d\tilde{r}. \tag{47}$$

Thus, one can find that near the horizon Eq. (41) reduces to

$$\mathcal{W}_{(\pm)}^{\mathcal{NH}} \approx \mathcal{E} \int \frac{1 \pm 1}{\tilde{Z}}d\tilde{r}. \tag{48}$$

It is easy to see that  $\mathcal{W}_{(-)}^{\mathcal{NH}} = 0$  (i.e., probability of ingoing phonons  $P_- = 1$ ), which warrants 100 % absorption of the ingoing phonons by the ABH. On the other hand, the integral of  $\mathcal{W}_{(+)}^{\mathcal{NH}}$  has a pole at the event horizon. To evaluate the associated integral, we use the Taylor series to expand the metric function  $\tilde{Z}$  around the horizon  $r_h$ :

$$\tilde{Z} \cong \tilde{Z}'(\tilde{r}_h)(\tilde{r} - \tilde{r}_h) + \mathcal{O}(\tilde{r} - \tilde{r}_h)^2. \tag{49}$$

Then, after deforming the contour around the pole  $r_h$ , we obtain

$$\begin{aligned} \mathcal{W}_{(+)}^{\mathcal{NH}} &\approx 2\mathcal{E} \int \frac{d\tilde{r}}{\tilde{Z}} \\ &\approx 2\mathcal{E} \int \frac{d\tilde{r}}{\tilde{Z}'(\tilde{r}_h)(\tilde{r} - \tilde{r}_h)} \\ &\approx i\pi\mathcal{E}\lambda_+\tilde{r}_h. \end{aligned} \tag{50}$$

The above result yields the tunneling probability of the outgoing phonons as follows

$$\begin{aligned} P_+ &= \exp(-2Im\mathcal{I}) \\ &= \exp[-2Im\mathcal{W}_{(+)}^{\mathcal{NH}}] \\ &= \exp(-2\pi\mathcal{E}\lambda_+\tilde{r}_h), \end{aligned} \tag{51}$$

which is also equal to the tunneling rate (since  $P_- = 1$ ):

$$\Gamma = \frac{P_+}{P_-} = \exp(-2\pi\mathcal{E}\lambda_+\tilde{r}_h). \tag{52}$$

After recalling the Boltzmann formula, which can be written as  $\Gamma = \exp(-\mathcal{E}/T)$ , we can read the horizon temperature of the ABH within the PGCs:

$$T = \frac{1}{2\pi\lambda_+\tilde{r}_h}. \tag{53}$$

The above result is in full agreement with the standard Hawking temperature (10). Meanwhile, from the first law of thermodynamics  $dE = T_H dS_{BH}$  one can derive the thermodynamic energy as

$$E = \frac{2\ln(\tilde{r}_h)}{\lambda_+}. \tag{54}$$

We also want to extend our computations to the tunneling method which considers the self-gravitation and back-reaction effects. To this end, we employ the PWTM (Parikh

and Wilczek 2000). In the PGCs, the radial null geodesics of a test particle are defined by

$$\dot{\tilde{r}}_{(\pm)} = \frac{d\tilde{r}}{dt} = \pm 1 - \sqrt{1 - \tilde{Z}}, \tag{55}$$

where positive (negative) sign stands for the outgoing (ingoing) geodesics. Hence, the near horizon radial outgoing null geodesics can be derived as

$$\begin{aligned} \tilde{r}_{(+)} &\cong 1 - \sqrt{1 - \tilde{Z}(\tilde{r}_h)} + \frac{1}{2} \frac{\tilde{Z}'(\tilde{r}_h)}{\sqrt{1 - \tilde{Z}(\tilde{r}_h)}} (\tilde{r} - \tilde{r}_h) \\ &\approx \kappa (\tilde{r} - \tilde{r}_h), \end{aligned} \tag{56}$$

where  $\kappa = \frac{\tilde{Z}'(\tilde{r}_h)}{2}$  is the surface gravity (Wald 1984). According to the PWTM, while the particle tunnels the event horizon from in ( $\tilde{r}_i$ ) to out ( $\tilde{r}_f$ ), the BH is supposed to emit a circular shell of energy  $\omega$  which is very small compared with the total (fixed) energy  $E$  i.e.,  $\omega \ll E$  (Parikh and Wilczek 2000). This event precipitates the energy of the ABH from  $E$  to  $E - \omega$ . Having regard to this self-gravitational effect (Kraus and Wilczek 1995a,b), the imaginary part of the action becomes (Mirekhtyari and Sakalli 2014; Zhang et al. 2008; Banerjee and Majhi 2008; Sakalli et al. 2011)

$$\begin{aligned} Im\mathcal{I} &= Im \int_{\tilde{r}_i}^{\tilde{r}_f} \int_E^{E-\omega} \frac{dH}{\tilde{r}_{(+)}} d\tilde{r}_{(+)} \\ &= -Im \int_{r_{in}}^{r_{out}} \int_0^\omega \frac{d\tilde{\omega}}{\tilde{r}_{(+)}} d\tilde{r}_{(+)}, \end{aligned} \tag{57}$$

where the Hamiltonian  $H = E - \tilde{\omega}$  ( $dH = -d\tilde{\omega}$ ). Using Eq. (56), one can evaluate the integral (57) by deforming the contour. Thus, one obtains

$$\begin{aligned} Im\mathcal{I} &= -\pi \int_0^\omega \frac{d\tilde{\omega}}{\kappa} = -\frac{1}{2} \int_0^\omega \frac{d\tilde{\omega}}{T_H} \\ &= -\frac{1}{2} \int_{S(E)}^{S(E-\omega)} dS \\ &= -\frac{1}{2} [S(E - \omega) - S(E)] \\ &= -\frac{1}{2} \Delta S. \end{aligned} \tag{58}$$

Herewith, the tunneling rate becomes (Parikh and Wilczek 2000)

$$\Gamma \sim e^{-2Im\mathcal{I}} = e^{\Delta S}. \tag{59}$$

If we re-set the universal gravitational constant to  $G(=l_p^2) = 1/8$  (keeping on  $c = \hbar = 1$ ), the entropy results in  $S = \frac{A_h}{4G} = 2A_h = 4\pi\tilde{r}_h$ : twice of the perimeter length of the horizon (see for example Banados et al. 1992, 1993; Akbar

2007). Then, ignoring the effect of the higher order GUP effects, Eq. (34) becomes (see also Zhang 2010)

$$S_{GUP} = 2A_h - \frac{\pi\alpha_{GUP}}{16\sqrt{2}} \ln(2A_h) + \mathcal{O}(\alpha_{GUP})^2. \tag{60}$$

With the aid of Eq. (54) one can re-express the event horizon as  $\tilde{r}_h = \exp(\frac{E}{2}\lambda_+)$ . Whence, we can obtain the change in the  $S_{GUP}$  as

$$\begin{aligned} \Delta S_{GUP} &= S_{GUP}(E - \omega) - S_{GUP}(E) \\ &= 4\pi \left[ \exp\left(\frac{E - \omega}{2}\lambda_+\right) - \exp\left(\frac{E}{2}\lambda_+\right) \right] \\ &\quad + \frac{\pi}{32\sqrt{2}} \alpha_{GUP} \lambda_+ \omega. \end{aligned} \tag{61}$$

When we expand Eq. (61) in the Taylor series with respect to  $\omega$  and accordingly arrange the terms up to the leading order in  $\omega$ , we get

$$\Delta S_{GUP} \cong -\left(\frac{1}{T_H} - \frac{\pi}{32\sqrt{2}} \alpha_{GUP} \lambda_+\right) \omega + O(\omega^2). \tag{62}$$

Using Eq. (59), we can define the QGC tunneling rate as

$$\Gamma^{QGC} \sim e^{\Delta S_{GUP}} = e^{-\frac{\omega}{T_H^{QGC}}}, \tag{63}$$

which yields the QGC Hawking temperature:

$$\begin{aligned} T_H^{QGC} &= \left(\frac{1}{T_H} - \frac{\pi}{32\sqrt{2}} \alpha_{GUP} \lambda_+\right)^{-1} \\ &= T_H \left(1 - \frac{\pi}{32\sqrt{2}} \alpha_{GUP} \lambda_+ T_H\right)^{-1} \\ &= T_H \left(1 - \frac{\alpha_{GUP}}{64\sqrt{2}\tilde{r}_h}\right)^{-1}. \end{aligned} \tag{64}$$

One can compare Eqs. (64) and (33) (with  $\Delta x = \frac{A_h}{\pi G} = \frac{8A_h}{\pi} = 16\tilde{r}_h$ ,  $\alpha_{GUP} \equiv \alpha_{GUP} l_p = \frac{\alpha_{GUP}}{2\sqrt{2}}$ , and taking cognizance of the leading order of  $\alpha_{GUP}$ ) to verify that both temperatures obtained are exactly the same. Furthermore, it is clear from Eq. (64) that ignorance of the back-reaction effects ( $\alpha_{GUP} = 0$ ) regains the standard Hawking temperature (10).

## 6 Conclusion

The HR of the rotating ABH in (2 + 1) dimensional space-time was thoroughly investigated in Li-Chun et al. (2011). However, it appears that GUP effects on that HR has not been thoroughly studied in the literature. In this paper, we have filled this gap by employing the KGE with GUP (11) and the GUP entropy (34). For simplicity, we have considered the rotating ABH in the dragging coordinate system.

Next, we have demonstrated that the KGE with GUP for a massive scalar field propagating in the background of an ABH completely separates with the HJ ansatz. Then, focusing on the quantum tunneling formalism, we have managed to find the GUP modified Hawking temperature (25) of the ABH. Utilizing the GUP entropy derived in Sect. 4, we have also obtained the QGC Hawking temperature (64). Both temperatures have the standard Hawking temperature limit when the GUP effect is terminated ( $\alpha_{GUP} = 0$ ).

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