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Hawking radiation as tunnelling from arbitrarily dimensional Reissner–Nordström de Sitter black hole*

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This paper extends Parikh–Wilzcek's recent work, which treats the Hawking radiation as a semi-classical tunnelling process from the event horizon of four dimensional Schwarzshild and Reissner–Nordström black holes, to that of arbitrarily dimensional Reissner–Nordström de Sitter black hole. The result shows that the tunnelling rate is related to the change of Bekenstein–Hawking entropy and the factually radiant spectrum is no longer precisely thermal after taking the dynamical black hole background and energy conservation into account, but is consistent with the underlying unitary theory and then satisfies the first law of the black hole thermodynamics. Meanwhile, in Parikh–Wilzcek's framework, this paper points out that the information conservation is only suitable for the reversible process but in highly unstable evaporating black hole (irreversible process) the information loss is possible.

Keywords: black hole radiation, tunnelling rate, Bekenstein–Hawking entropy, first law of the black hole thermodynamics

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1. Introduction

The 'no hair' theorem stated that all information about the collapsing body was lost from the outside region apart from three conserved quantities: the mass, the angular momentum, and the electric charge. However, taking the quantum effect into consideration, we know that the situation is changed. In 1975, Hawking discovered that black holes can radiate thermally, with the emission of thermal radiation, black holes can lose energy, shrink and eventually evaporate away completely.[1] Since the radiation with a precisely thermal spectrum has no way to be recovered after black holes have disappeared completely, hence it arouses a disturbing and difficult problem: what happens for information during the black hole evaporation? Hawking and Kip Torne thought that information is lost in black hole evaporation. But, John Preskill believed that information is not lost and can get out of the black hole. In 2005, Hawking changed his opinion and argued that information can indeed get out of the black hole,[2] which is partly based on the Parikh–Wilzcek's recent work that treats the Hawking radiation as tunnelling process and applies the semi-classical method to give out the factual radiation as not exactly thermal but subtle correction to the Hawking precisely thermal spectrum.

In fact, the background spacetime of black holes varies with the loss of energy due to the radiation of black holes. But till now, most methods for deriving Hawking radiation spectrum are based on a fixed background, and do not consider the fluctuation for the geometry of the space–time.[3−9] At present, a program that implemented Hawking radiation as a tunnelling process was initiated by Kraus and Wilczek and developed by Parikh and Wilzcek who carried out a dynamical treatment of black hole geometries.[10−12] More specifically, they considered the effects of a positive energy matter shell propagating outwards through the horizon of the Schwarzshild and Reissner–Nordström

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black holes, and incorporated the self-gravitation correction of the radiation. Following that, Hemming and Keski–Vakkuri have investigated the Hawking radiation from the event horizon of Anti-de Sitter black hole,[13] and Medved has researched into that from a de Sitter black hole[14] which is motivated at least by the following two aspects: firstly, recent analysis of astronomical data for supernovae indicates that there is a positive cosmological constant in our universe, it has been suggested that our universe will asymptotically approach a de Sitter space–time, thus a sense of urgency in resolving the quantum-gravitational mysteries of de Sitter space has been sparked. Secondly, defined in a manner analogous to the AdS/CFT correspondence, an interesting proposal, the so-called dS/CFT correspondence, has been suggested recently that there is a duality between quantum gravity on a dS space and a Euclidean conformal field on a boundary of the dS space. However, although there has been considerable success along this line, the proposed duality is still marred by various ambiguities such as a dual boundary theory that appears to be non-unitary, the conspicuous absence of measurable quantities and logistic breakdowns that can be attributed to the infinite entropy of de Sitter space. Hence it may be an appropriate juncture to 'take a step back' and reinforce our understanding of de Sitter space at a semi-classical level. With this as our mindset, de Sitter radiation as a semi-classical tunnelling process advances the quantum gravity on a dS space and a Euclidean conformal field on a boundary of the dS space.

For another, the emission spectra that Parikh and Wilzcek calculated for black holes give a leading-order correction to the emission rate arising from loss of mass of the black holes, which corresponds to the energy carried by the radiated quantum. The result displays that the derived spectrum of black hole radiation is no longer strictly pure thermal under the consideration of the energy conservation and the unfixed space–time background, which may be a correct amendment to Hawking radiation spectrum.

Recently, Zhang investigated the Parikh–Wilzcek tunnelling framework and argued that the Parikh–Wilzcek work is only suitable for a reversible process,[15] which asserted that the tunnelling rate is consistent with an underlying unitary theory and satisfies the first law of the black hole thermodynamics. The above mentioned process is reversible and the derived result is considered to be a support to the information conservation attributed ultimately to the underlying unitary theory. But, in fact, the factual emission process is irreversible, because an evaporating black hole is highly unstable, thus the unitary theory will not be satisfied and the information loss is possible.

Combined with these reasons, the purpose of the current paper is to present a reasonable extension of the Parikh–Wilczek semi-classical tunnelling method in a spherically symmetric space–time in four dimensions to the case of an arbitrarily dimensional Reissner–Nordström black hole in de Sitter space–time. Moreover, we investigate the Hawking radiation via tunnelling from the event horizon (EH) and the cosmological horizon (CH), where a coordinate system that is well-behaved at the horizons is introduced, and meanwhile the first law of the black hole thermodynamics for the reversible process is presented, and point out that the information conservation is only suitable to the reversible process and in highly unstable evaporating black hole (irreversible process) the information loss is possible.

The remainder of this paper is outlined as follows. In Section 2, we introduce a Painlevé–Reissner–Nordström de Sitter coordinate system and present the radial null geodesic. In Sections 3 and 4, Hawking radiation via tunnelling from the EH and the CH is investigated, and the tunnelling rates from the two horizons are obtained. Finally, we give some discussion about our results and discover that the information conservation is only suitable to the reversible process and in highly unstable evaporating black hole (irreversible process) the information loss is possible.

2. Painlevé coordinate transformation and the radial null geodesics

The line element of arbitrarily dimensional Reissner–Nordström–de Sitter black hole is[16]

$$\mathrm{d}s^2 = -f\left(r\right)\mathrm{d}t_R^2 + f^{-1}\left(r\right)\mathrm{d}r^2 + r^2\mathrm{d}\Omega_n^2, \qquad (1)$$

where

$$f\left(r\right) = 1 - \frac{\omega_n M}{r^{n-1}} + \frac{n\omega_n^2 Q^2}{8\left(n-1\right)r^{2n-2}} - \frac{r^2}{l^2},$$

$$\omega_n = \frac{16\pi G}{n\mathrm{Vol}\left(S^n\right)}, \qquad (2)$$

here G is the gravitational constant in $(n+2)$ dimensions, l is the radius of curvature of dS space, $\mathrm{Vol}\left(S^n\right)$

denotes the volume of a unit n-sphere $\mathrm{d}\Omega_n^2$. For general M and Q, the equation $f(r)=0$ may have four real roots. Three of them are real: the largest one is the CH r_{c}, the smallest is the inner horizon r_-, and the middle one is the EH r_+ of the black hole. And the fourth is r_0 which is negative and has no physical meaning. Throughout the following study, the units $G=c=\hbar=1$ are used. Obviously, at the horizons, there exists a coordinate singularity in the metric (1), to remove the coordinate singularity, performing a Painlevé-like coordinate transformation[17−21]

$$\mathrm{d}t_R=\mathrm{d}t\pm\frac{\sqrt{1-f(r)}}{f(r)}\mathrm{d}r, \tag{3}$$

we obtain the Painlevé–Reissner–Nordström de Sitter black hole in arbitrary dimensions as

$$\mathrm{d}s^2=-f(r)\,\mathrm{d}t^2\pm2\sqrt{1-f(r)}\mathrm{d}t\mathrm{d}r+\mathrm{d}r^2+r^2\mathrm{d}\Omega_n^2, \tag{4}$$

where the +(−) sign denotes the space–time line element of the outgoing (ingoing) particle across the EH and the CH respectively. Obviously, the Painlevé–Reissner–Nordström de Sitter black hole in arbitrary dimensions possesses many attractive properties: (i) the new form of the line element is stationary, but not static, so the time direction remains to be a Killing vector; (ii) the metric is regular at the horizons of the black hole; (iii) the time coordinate t represents the local proper time for radially free-falling observers; (iv) the measure on the surfaces of constant-time slices is the same as that of flat space–time; (v) it satisfies Landau's condition of coordinate clock synchronization. These attractive characters are very advantageous for us to investigate the tunnelling radiation of the particle across the horizons and to do an explicit computation of the tunnelling probability at the horizons.

Now, let us work with the new form (4) and obtain the radial null geodesics of the mass-less particle as

$$\dot{r}=\frac{\mathrm{d}r}{\mathrm{d}t}=\pm1\mp\sqrt{1-f(r)}, \tag{5}$$

where the +(−) sign in the first item can be identified with the outgoing (ingoing) radial motion, and the −(+) sign in the second item denotes the same meaning as the +(−) sign in Eq.(4) respectively.

In the following two sections, the tunnelling rates of the particle at the EH and the CH are obtained. Since the overall picture of tunnelling radiation for the metric is involved, to simplify the discussion we will consider the outgoing radiation from the EH, and ignore the incoming radiation from the CH when the tunnelling characteristics of the EH is discussed. However, dealing with the CH cases, we only consider the incoming radiation from the CH, and ignore the outgoing radiation from the EH.

3. Tunnelling rate at the EH

Now, we turn to discuss Hawking radiation of the particle as a semi-classical tunnelling process across the horizons. We adopt the picture of a pair of virtual particles spontaneously created just inside the horizon. The positive energy virtual particle can tunnel out and materialize as a real particle escaping classically to infinity, its negative energy partner is absorbed by the black hole, resulting in a decrease in the mass of the black hole. In our discussion, we consider the emitted particle of energy ω. If the particle's self-gravitation is taken into account, Eqs.(4) and (5) should be modified. Taking the energy conservation into consideration, and when the particle of energy ω tunnels out of the EH, we find that the mass parameter in Eqs.(4) and (5) will be replaced with $M\to M-\omega$. So the radial null geodesics of the particle tunnelling out from the EH is

$$\dot{r}=1-\sqrt{1-\tilde{f}(r)}, \tag{6}$$

where

$$\tilde{f}(r)=1-\frac{\omega_n(M-\omega)}{r^{n-1}}+\frac{n\omega_n^2Q^2}{8(n-1)r^{2n-2}}-\frac{r^2}{l^2}. \tag{7}$$

Since the EH and the infinite red-shift surface are coincident with each other, the geometrical optical limit becomes an especially reliable approximation and the semi-classical WKB approximation can be used. In WKB approximation, the probability of tunnelling is related to the imaginary part of the action via[22]

$$\Gamma\sim\mathrm{e}^{-2\mathrm{Im}S}, \tag{8}$$

where

$$\mathrm{Im}S=\mathrm{Im}\int_{t_{\mathrm{i}}}^{t_{\mathrm{f}}}L\mathrm{d}t=\mathrm{Im}\int_{r_{\mathrm{i}}}^{r_{\mathrm{f}}}\int_0^{P_r}\mathrm{d}P_r'\mathrm{d}r, \tag{9}$$

where r_{i} and r_{f} represent the locations of the EH before and after the particle of energy ω tunnels out, and P_r is the canonical momentum conjugated to the coordinate r. Substituting Hamilton's canonical equation of motion

$$\dot{r}=\left.\frac{\mathrm{d}H}{\mathrm{d}P_r}\right|_r,\quad \mathrm{d}H=\mathrm{d}(M-\omega)=-\mathrm{d}\omega, \tag{10}$$

into Eq.(9), and switching the order of integration, we get the imaginary part of the action

$$\begin{aligned}\mathrm{Im}S =&\mathrm{Im}\int_{r_\mathrm{i}}^{r_\mathrm{f}}\int_{M}^{M-\omega}\frac{1}{\dot{r}}\mathrm{d}\left(M-\omega'\right)\mathrm{d}r\\ =&\mathrm{Im}\int_{M}^{M-\omega}\int_{r_\mathrm{i}}^{r_\mathrm{f}}\frac{1}{1-\sqrt{1-f'\left(r\right)}}\mathrm{d}\left(M-\omega'\right)\mathrm{d}r,\end{aligned}\tag{11}$$

where

$$\begin{aligned}f'\left(r\right)=&1-\frac{\omega_n\left(M-\omega'\right)}{r^{n-1}}+\frac{n\omega_n^2Q^2}{8\left(n-1\right)r^{2n-2}}-\frac{r^2}{l^2}\\ =&\frac{1}{l^2r^{2n-2}}\left(r-r'_+\right)\left(r-r'_-\right)\left(r'_\mathrm{c}-r\right)\left(r-r'_0\right),\end{aligned}$$

in which, the mass parameter in r'_+, r'_-, r'_0 and r'_c are $M-\omega'$. The above integral can be evaluated by deforming the contour around the single pole $r=r'_+$ at the EH. Doing the r integral first, we find

$$\begin{aligned}\mathrm{Im}S=&-\pi\mathrm{Im}\int_{M}^{M-\omega}\frac{2l^2r'^{2n-2}_+}{\left(r'_+-r'_-\right)\left(r'_\mathrm{c}-r'_+\right)\left(r'_+-r'_0\right)}\\ &\times\mathrm{d}\left(M-\omega'\right).\end{aligned}\tag{12}$$

Using the identity

$$\begin{aligned}&\left(r'_+-r'_-\right)\left(r'_\mathrm{c}-r'_+\right)\left(r'_+-r'_0\right)\frac{1}{\omega_nl^2r'^{n-1}_+}\mathrm{d}r'_+\\ =&\mathrm{d}\left(M-\omega'\right),\end{aligned}\tag{13}$$

we can easily finish the integration and obtain

$$\mathrm{Im}S=-\pi\mathrm{Im}\int_{r_\mathrm{i}}^{r_\mathrm{f}}\frac{2}{\omega_n}r_+^{n-1}\mathrm{d}r_+=-\frac{2\pi}{n\omega_n}\left(r_\mathrm{f}^n-r_\mathrm{i}^n\right).\tag{14}$$

So the tunnelling rate across the EH is

$$\Gamma\sim\mathrm{e}^{-2\mathrm{Im}S}=\mathrm{e}^{\frac{4\pi}{n\omega_n}\left(r_\mathrm{f}^n-r_\mathrm{i}^n\right)}=\mathrm{e}^{\Delta S_\mathrm{BH}},\tag{15}$$

where $\Delta S_\mathrm{BH}=S_\mathrm{BH}\left(M-\omega\right)-S_\mathrm{BH}\left(M\right)$ is the difference of Bekenstein–Hawking entropy at the EH, and $S_\mathrm{BH}=\dfrac{r_+^n\mathrm{Vol}\left(S^n\right)}{4}=\dfrac{4\pi r_+^n}{n\omega_n}$ is the Bekenstein–Hawking entropy at the EH. Obviously, the derived emission spectrum actually deviates from pure thermality, and this result consists with an underlying unitary theory and perfectly generalizes those obtained by Parikh and Wilczek.

We have investigated that the emission process satisfies the first law of the black hole thermodynamics. According to the definition of the surface gravity for the horizon, that is

$$\begin{aligned}\kappa'_+=&-\frac{1}{2}\lim_{r\to r'_+}\sqrt{\frac{-g^{11}}{g^{00}}}\frac{\partial}{\partial r}\ln\left(-g^{00}\right)\\ =&\frac{1}{2l^2r'^{2n-2}_+}\left(r'_+-r'_-\right)\left(r'_+-r'_0\right)\left(r'_\mathrm{c}-r'_+\right),\end{aligned}\tag{16}$$

so Eq.(12) can be rewritten as

$$\begin{aligned}\mathrm{Im}S=&-\frac{1}{2}\int_{M}^{M-\omega}\frac{1}{T'_+}\mathrm{d}\left(M-\omega'\right)\\ =&-\frac{1}{2}\int_{S_\mathrm{BH}(M)}^{S_\mathrm{BH}(M-\omega)}\mathrm{d}S'=-\frac{1}{2}\Delta S_\mathrm{BH}\\ =&-\frac{2\pi}{n\omega_n}\left(r_\mathrm{f}^n-r_\mathrm{i}^n\right),\end{aligned}\tag{17}$$

where

$$\begin{aligned}T'_+=&\frac{\kappa'_+}{2\pi}=\frac{1}{4\pi l^2r'^{2n-2}_+}\\ &\times\left(r'_+-r'_-\right)\left(r'_+-r'_0\right)\left(r'_\mathrm{c}-r'_+\right),\end{aligned}\tag{18}$$

is the Hawking temperature of the EH after the particle emission. So from Eq.(17), we can easily find the differential form of the first law of the black hole thermodynamics

$$\mathrm{d}M'=T'_+\mathrm{d}S',\tag{19}$$

where $M'=M-\omega'$. Obviously, Parikh–Wilczek's semi-classical tunnelling formalism is so successful that it satisfies the first law of the black hole thermodynamics.

4. Tunnelling rate at the CH

In this section, we shall calculate the tunnelling rate at the CH. Different from the tunnelling behaviour across the EH, the particle is found to tunnel into the CH. Ignoring the effect of the EH and taking energy conservation into consideration, when the particle of energy ω tunnels into the CH, we will replace the mass parameter M in Eqs.(4) and (5) by $M+\omega$. For the moment, the radial null geodesics of the particle tunnelling into the CH is

$$\dot{r}=-1+\sqrt{1-\hat{f}\left(r\right)},\tag{20}$$

where

$$\hat{f}\left(r\right)=1-\frac{\omega_n\left(M+\omega\right)}{r^{n-1}}+\frac{n\omega_n^2Q^2}{8\left(n-1\right)r^{2n-2}}-\frac{r^2}{l^2}.\tag{21}$$

According to the calculation of the imaginary part of the particle action at the EH, we can find that at the CH

$$\begin{aligned}\mathrm{Im}S=&-\mathrm{Im}\int_{r_\mathrm{ic}}^{r_\mathrm{fc}}\int_{M}^{M+\omega}\frac{1}{\dot{r}}\mathrm{d}\left(M+\omega'\right)\mathrm{d}r\\ =&-\mathrm{Im}\int_{r_\mathrm{ic}}^{r_\mathrm{fc}}\int_{M}^{M+\omega}\frac{1}{-1+\sqrt{1-f''\left(r\right)}}\\ &\times\mathrm{d}\left(M+\omega'\right)\mathrm{d}r,\end{aligned}\tag{22}$$

where Hamilton's canonical equation of motion is $\dot{r} = \left.\frac{\mathrm{d}H}{\mathrm{d}P_r}\right|_r$, $\mathrm{d}H = -\mathrm{d}\left(M+\omega\right)$ is used at the CH, r_{ic} and r_{fc} are the location of the CH before and after the particle tunnels into the CH respectively, and

$$\begin{aligned} f''\left(r\right) =& 1-\frac{\omega_n\left(M+\omega'\right)}{r^{n-1}}+\frac{n\omega_n^2Q^2}{8\left(n-1\right)r^{2n-2}}-\frac{r^2}{l^2} \\ =& \frac{1}{l^2r^{2n-2}}\left(r-r''_+\right)\left(r-r''_-\right)\left(r''_{\mathrm{c}}-r\right)\left(r-r''_0\right), \end{aligned}$$

here, the mass parameter corresponding to r''_+, r''_-, r''_0 and r''_{c} are $M+\omega'$. Carrying on the above similar calculation for Eq.(22), we have

$$\begin{aligned} \mathrm{Im}S =& -\frac{1}{2}\int_M^{M+\omega}\frac{1}{T''_{\mathrm{c}}}\mathrm{d}\left(M+\omega'\right) \\ =& -\frac{1}{2}\int_{S_{\mathrm{CH}}(M)}^{S_{\mathrm{CH}}(M+\omega)}\mathrm{d}S'' = -\frac{1}{2}\Delta S_{\mathrm{CH}} \\ =& -\frac{2\pi}{n\omega_n}\left(r_{\mathrm{fc}}^n-r_{\mathrm{ic}}^n\right), \end{aligned} \tag{23}$$

where $\Delta S_{\mathrm{CH}} = S_{\mathrm{CH}}\left(M+\omega\right)-S_{\mathrm{CH}}\left(M\right)$ is the change of Bekenstein–Hawking entropy at the CH, and

$$\begin{aligned} T''_{\mathrm{c}} =& \frac{\kappa''_{\mathrm{c}}}{2\pi}=\frac{1}{4\pi l^2{r''}_{\mathrm{c}}^{2n-2}} \\ & \times\left(r''_{\mathrm{c}}-r''_-\right)\left(r''_{\mathrm{c}}-r''_0\right)\left(r''_{\mathrm{c}}-r''_+\right), \end{aligned} \tag{24}$$

is the temperature of the CH after the particle tunnels into it. So the first law of the black hole thermodynamics

$$\mathrm{d}M'' = T''_{\mathrm{c}}\mathrm{d}S'' \tag{25}$$

is satisfied, where $M''=M+\omega'$. Thus further research indicates that Parikh–Wilczek's semi-classical tunnelling method successfully proves the conservation of information of the black hole. The factual spectrum is no longer precisely thermal, and the tunnelling rates at the EH and CH, which satisfy the first law of the black hole thermodynamics, are related to Bekenstein–Hawking entropy, but are consistent with the underlying unitary theory. However, the success of Parikh–Wilczek's semi-classical tunnelling framework is only suitable for a reversible process, which is left to Section 5 for discussions.

5. Discussions

Although Parikh and Wilczek treated Hawking radiation as a tunnelling process and give a semi-classical but the first explicit calculation about the information conservation, the framework, which satisfies the first law of the black hole thermodynamics and consists with an underlying unitary theory, is only suitable for the reversible process and proves the information conservation. Equations (19) and (25) are the differential form of the first law of the black hole thermodynamics, which is combined with the energy conservation law $\mathrm{d}M = \mathrm{d}Q_h$ (where Q_{h} is the heat quantity) and the second law of the black hole thermodynamics $\mathrm{d}S = \frac{\mathrm{d}Q_{\mathrm{h}}}{T}$ (where S is the entropy of the black hole). The equation of energy conservation is suitable for the reversible or the irreversible process, but the second law of the black hole thermodynamics $\mathrm{d}S = \frac{\mathrm{d}Q_{\mathrm{h}}}{T}$ is only reliable for the reversible process. But in fact, the existence of the negative heat capacity, an evaporating black hole is a highly unstable system, and the thermal equilibrium between the black hole and the outside is unstable, there will be difference in temperature, so the process is irreversible, and for the moment the second law of the black hole thermodynamics should be $\mathrm{d}S > \frac{\mathrm{d}Q_{\mathrm{h}}}{T}$. Thus the underlying unitary theory is not satisfied here, and therefore the information loss is possible during the evaporation, and the Parikh–Wilczek's tunnelling framework cannot prove the information conservation.

For another, the preceding study is still a semi-classical analysis, which means that the radiation should be treated as point particles. Such an approximation can only be valid in the low energy regime. If we properly address the information loss problem, then a better understanding of physics at the Planck scale is a necessary prerequisite, especially that of the last stages of Hawking evaporation.

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