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Black hole as coherent signal amplifier

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Abstract In a recent analysis (Misra et al. in npj Quantum Inf 10:34, 2024. 10.1038/s41534-024-00817-w), it has been shown that Hawking radiation is the main source of energy to empower a coherent signal pulse. In this work, we have explored the same effect for a case where the time derivative of the scalar field mode of the redirected Hawking radiation appears explicitly in the interaction Hamiltonian. We have considered a stream of two-level atoms falling freely towards the event horizon of a black hole. The Hawking radiation redirected from an orbiting mirror interacts with the atoms which make a transition between the ground state and the excited state through the emission of a signal photon. The signal pulse is amplified by the mechanical work done by the redirected Hawking mode. The whole set up works as a black hole powered quantum heat engine. We have shown that this amplification depends on the frequency of both the signal mode and the Hawking mode, the flux of the redirected Hawking mode and the lapse function of the black hole. In contrast to the result obtained in Misra et al. (npj Quantum Inf 10:34, 2024. 10.1038/s41534-024-00817-w), we observe in our analysis, that due to the coupling of the momentum degrees of freedom of the Hawking radiation modes with the freely falling detector, the power output depends inversely with the lapse function of the black hole and is proportional to the frequency of the emitted Hawking radiation. As a result the maximum output power enhances significantly if the atom is very close to the event horizon of the black hole. We have analyzed this effect for two types of detectors attached to the cavity. At first we considered a point-like detector and then we have done the analysis from the perspective of a detector with smearing.

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1 Introduction

The connection between quantum field theory and general theory of relativity is one of the most insightful areas of exploration in the foundation of modern theoretical physics. After the historic development of general relativity by Albert Einstein [1,2], the interplay between thermodynamics and general relativity has been remarkable to the theoretical physicists for the impactful consequences like black hole entropy [3–6], quantum coherence [7–9], and acceleration radiation [10–13]. The study of acceleration radiation emitted from a two-level atom freely falling into the event horizon of a black hole has an important aspect in recent times [14,15].
In [14], the authors proposed a theoretical scenario where a cloud of two-level atoms is freely falling into the event horizon of the Schwarzschild black hole and they emit acceleration radiation after interacting with the gravitational field of the black hole. It causes the horizon brightened acceleration radiation (HBAR) entropy of the black hole. This entropy is similar to the usual Bekenstein–Hawking entropy [3–6,16]. This similarity shows the connection between quantum optics and general relativity [14,17]. There have been further analysis that extends this idea of HBAR entropy for different black hole geometries [18–27]. In these cases, a mirror is placed in the event horizon of the respective black hole to shield the Hawking radiation. These analyses provide insights into the equivalence principle between gravity and acceleration.
However, in a very recent work [15], the authors went beyond this consideration and allowed the Hawking radiation to interact with the infalling atoms. This study showed that the Hawking radiation acts as a coherent light amplifier. It transfers coherent energy to the signal photon emitted by the atoms. Unlike other energies like heat, this coherent energy exhibits mechanical work, a technical term of which is ergotropy [28–42], and helps to amplify the signal pulse of light quanta.

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According to quantum field theoretic concept, from the perspective of an infalling observer, Unruh vacuum [14,21,22,43] exists near the black hole horizon. Although a distant observer sitting at infinity can detect the flux of particles emitting outward from the black hole due to the quantum fluctuations happening in the near event horizon area of the black hole. This outgoing particle stream is identified as the Hawking radiation. But it cannot directly excite the infalling atoms, rather if a mirror is placed in a stable orbit at a fixed distance, then the reflected Hawking radiation can do that. This atom-field interaction resembles to the anti-resonant Raman process where the atom makes transition from the ground state $|g\rangle$ to the excited state $|e\rangle$ by simultaneous emission of signal photon with frequency ν. This whole system can be thought of as the quantum heat engine which is being empowered by the gravitational field of the black hole. Here the signal photon mode acts as the piston of the heat engine and the redirected Hawking mode is the heat bath. In [15] and our present analysis, the Hawking radiation is the main source of coherent energy for the signal mode. Although the kinetic energy of the ground state two-level atoms can also be used as coherent signal amplifier [44].

The motivation of our present analysis lies in the fact that we have considered the derivative coupling, whereas in [15] the atom-field interaction Hamiltonian has the form

$$\hat{H}_{int} = g_h \phi_h \hat{b}^{\dagger} \hat{a}_h |e\rangle\langle g| + H.C. \tag{1}$$

Here the Hawking field mode ϕ_h is minimally coupled with the infalling atoms. This scenario resembles to the standard Unruh–Fulling effect [45,46]. In this effect, there is inbuilt infrared (IR) divergence problem which arises due to the minimal coupling of a scalar field [47–49]. In some analyses [48–53], it is shown that this IR problem can be removed if the derivative of the scalar field interacts with the detector. As discussed in [49], the Unruh–DeWitt detector executes uniform circular motion with a field initially in thermal state and the effect due to the acceleration radiation can be detected. Apart from these, in a recent work [54], the derivative coupling between the scalar field and the detector has been considered to explain the HBAR entropy. Taking the motivations from the previously mentioned works, we have implemented the concept of derivative coupling in our present analysis. Here, we have considered two cases. In the first case, we consider a point-like detector coupled with the time derivative of the redirected Hawking field mode. This redirected Hawking mode provides energy to amplify the signal photons emitted due to the interaction. In the second part, we have repeated the same analysis with a detector having smearing. This also gives the same dependence of atomic frequency and signal frequency.

This paper is arranged as following. In Sect. 2, we demonstrate the interaction between atom and the scalar field mode of the redirected Hawking radiation examined by a point-like detector attached with the cavity. We calculate the ergotropy which signifies the maximum power gain of the signal pulse of light quanta. In Sect. 3, we repeat the same analysis for a detector with smearing. In Sect. 4, we discuss the important findings of the whole analysis.

2 Excitation of atoms by redirected hawking radiation examined by point-like detector

In this work, we have considered the thought experiment mentioned in [15]. A stream of two-level atoms is freely falling into the gravitational field of the black hole and interacts with the Hawking radiation emitted from the black hole. Initially the atoms are in the ground state and hence there are no photons. This assures that the field is in Unruh vacuum. Now the excitation of the atoms can be initiated by considering outgoing Rindler photons which fill the vacuum and constitute the Hawking radiation. But the atoms cannot get excited by the Hawking radiation directly emitted from the black hole. So a mirror is placed at a fixed distance from the event horizon of the black hole at $r = r_0$ with $r_0 > 3r_s$ where r_s is the Schwarzschild radius. The redirected Hawking radiation from the mirror can excite the atoms. This works as a coherent amplifier of the signal mode.

The coupling between the two-level atoms and the redirected Hawking mode is defined by the interaction Hamiltonian for a point-like detector given by [55]

$$\hat{\mathscr{H}}_{\text{int}} = \mathscr{G}|e\rangle\langle g|\hat{b}_s^{\dagger}\hat{a}_h\sqrt{-g}\; g^{00}\partial_0\phi_h(t, r_*) + H.C. \tag{2}$$

where $\mathscr{G}$ denotes the atom-scalar field coupling strength, $|g\rangle$ and $|e\rangle$ are the ground state and excited state of the two-level atom respectively, $\hat{b}_s^{\dagger}$ is the creation operator for signal photon and $\hat{a}_h$ is the annihilation operator for the heat bath mode. This interaction Hamiltonian has the term g^{00} which contains the information about the black hole and has the form $g^{00} = \frac{1}{f(r)}$ with $f(r)$ being the lapse function of the black hole. Since the atoms are falling along a radial direction, we restrict our analysis to a (1+1)-dimensional spacetime. In this reduced setting, the determinant of the metric tensor satisfies $\det(g_{\mu\nu}) = -1$, so that $\sqrt{-g} = 1$. This form of the Hamiltonian is the basic difference between [15] and our analysis. In the Hamiltonian, $\partial_0\phi_h(t, r_*)$ denotes the time derivative of the scalar field mode corresponding to the redirected Hawking radiation ϕ_h , the form of which reads as following [15]

$$\phi_h(t, r_*) = e^{-\frac{i\Omega_h}{2}(t-r_*)} - e^{i\Omega_h(r_0+\ln(r_0-1))}e^{-\frac{i\Omega_h}{2}(t+r_*)} \tag{3}$$

where r_* is the Regge–Wheeler coordinate for Schwarzschild black hole written as $r_* = \int \frac{dr}{f(r)} = r + \ln(r-1)$ and

r_0 is the radius of the mirror orbit. In the atom-scalar field interaction, the redirected Hawking radiation is converted into the signal photon by the atomic transition between two levels. Our main goal is to find the energy gain of the signal mode.

Assuming $|n_s\rangle$ and $|n_h\rangle$ to be the Fock states for the signal mode and the redirected Hawking radiation mode, the basis for the atom-field combined states can be defined as

$$|1\rangle = |g, n_s, n_h\rangle$$
$$|2\rangle = |e, n_s+1, n_h-1\rangle \; . \tag{4}$$

Initially the atom is in ground state and the signal photon is in n_s state. The combined state of the total system at a certain time t can be written in terms of the superposition of basis states as

$$|\psi\rangle = u(t)|1\rangle + v(t)|2\rangle \tag{5}$$

where $C_1(t)$ and $C_2(t)$ are the time dependent coefficients which satisfy the initial conditions

$$u(t=0) = 1, \;\; v(t=0) = 0 \; . \tag{6}$$

Now we shall find the expression for the coefficients using Schrödinger's equation in the interaction picture. So, we can rewrite the Hamiltonian in Eq. (2) in interaction picture as[1]

$$\mathscr{H}_{int}^{(I)} = i\hbar\mathscr{G}\Omega_h \frac{1}{f(r)}\Big[\hat{b}_s^\dagger \hat{a}_h \phi_h(t, r_*)|e\rangle\langle g|e^{i\beta t} - \hat{b}_s \hat{a}_h^\dagger \phi_h^*(t, r_*)|g\rangle\langle e|e^{-i\beta t}\Big] . \tag{7}$$

Here we have put the expression of $\partial_0\phi_h(t, r_*)$ obtained using Eq. (3) as $\partial_0\phi_h(t, r_*) = -\frac{i\Omega}{2}\phi_h(t, r_*)$ and $\beta = (\nu+\omega_0-\Omega_h)$ where ν is the frequency of signal mode and ω_0 is the resonant frequency of two-level atoms.

Now our aim is to find two coefficients $u(t)$ and $v(t)$. From the Schrödinger's equation along with Eqs. (5) and (7), one can write

$$i\hbar\frac{\partial|\psi\rangle}{\partial t} = \mathscr{H}_{int}^{(I)}|\psi\rangle$$
$$\Rightarrow \begin{pmatrix}\dot{u}(t)\\ \dot{v}(t)\end{pmatrix} = \begin{pmatrix}-\frac{\Omega_h\mathscr{G}}{f(r)}\phi_h^* e^{i\beta t} v(t)\\ \frac{\Omega_h\mathscr{G}}{f(r)}\phi_h e^{-i\beta t} u(t)\end{pmatrix} . \tag{8}$$

From this equation, we have the relations between two coefficients as

$$\dot{u}(t) = -\Omega_h\mathscr{G}\,\eta(r)\phi_h^* e^{-i\beta t} v(t) \tag{9}$$

$$\dot{v}(t) = \Omega_h\mathscr{G}\,\eta(r)\phi_h e^{i\beta t} u(t) \tag{10}$$

where $\eta(r) = \frac{1}{f(r)}$. Solving these equations along with the initial conditions mentioned in Eq. (6), we obtain the form of the coefficients as

$$u(t) = e^{-\frac{-it}{2}(\beta-\frac{\Omega_h}{2})}\Bigg[\cos\left(\frac{t}{2}\sqrt{\left(\beta-\frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\right) + \frac{i\left(\beta-\frac{\Omega_h}{2}\right)\sin\left(\frac{t}{2}\sqrt{(\beta-\frac{\Omega_h}{2})^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\right)}{\sqrt{\left(\beta-\frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}}\Bigg],$$
$$v(t) = \frac{2\mathscr{G}\Omega_h\phi_h\eta e^{\frac{-it}{2}(\beta-\frac{\Omega_h}{2})}}{\sqrt{\left(\beta-\frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}} \sin\left(\frac{t}{2}\sqrt{\left(\beta-\frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\right) . \tag{11}$$

Now we are aiming to find out the change of ergotropy of the signal mode. The ergotropy of the signal mode is defined as [15]

$$\mathscr{E} = Tr(\rho_s\mathscr{H}_s) - Tr(\hat{U}\rho_s\hat{U}^\dagger\mathscr{H}_s) \tag{12}$$

where ρ_s is the density operator corresponding to the signal state and $\mathscr{H}_s$ is the Hamiltonian of the signal with frequency ν, defined as

$$\mathscr{H}_s = \hbar\nu\hat{b}_s^\dagger\hat{b}_s \; . \tag{13}$$

The unitary operator $\hat{U}$ in Eq. (12) transforms the signal states as $\hat{U}|n_s\rangle \rightarrow |0\rangle$ and $\hat{U}|n_s+1\rangle \rightarrow |1\rangle$.[2]

Initially, the signal is in the state $\rho_s^{(i)} = |n_s\rangle\langle n_s|$ and the atom is in the state $\rho_{atom}^{(i)} = |g\rangle\langle g|$. After the transition of atom occurs to its excited state, a photon is added to the signal mode from the Hawking mode and hence the final state of the combined system is defined by

$$\rho^{(f)} = |\psi\rangle^{(f)}\langle\psi|^{(f)}$$
$$= (u(t)|g, n_s, n_h\rangle + v(t)|e, n_s+1, n_h-1\rangle)$$
$$(u^*(t)\langle g, n_s, n_h| + v^*(t)\langle e, n_s+1, n_h-1|) \tag{14}$$

Now if we trace out the Hawking radiation mode from this state, then the state will have the form $\rho = (|u|^2|gr, n_s\rangle\langle g, n_s| + |v|^2|e, n_s+1\rangle\langle e, n_s+1|)$. Now tracing out the atom, the final state of the signal is $\rho_s^{(f)} = \big(|u|^2|n_s\rangle\langle n_s| + |v|^2|n_s+1\rangle\langle n_s+1|\big)$ with $|u|^2+|v|^2 = 1$. In a similar way, the final state of the atom is $\rho_{atom}^{(f)} = |u|^2|g\rangle\langle g| + |v|^2|e\rangle\langle e|$.

[1] "I" in the superscript denotes the interaction picture.

[2] This $|1\rangle$ is not the same as $|gr, n_s, n_h\rangle$. This is the single photon state.

The gain of ergotropy of the signal mode between this transformation is obtained as[3]

$$\mathscr{E}_{\text{gain}} = \mathscr{E}^{(f)} - \mathscr{E}^{(i)} = \hbar\nu(|v|^2 - |u|^2)\,. \tag{15}$$

Substituting the coefficients from Eq. (11), we obtain the gain as

$$\begin{aligned}\mathscr{E}_{\text{gain}} = \hbar\nu\Bigg[&\frac{\left(4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2 - \left(\beta - \frac{\Omega_h}{2}\right)^2\right)}{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\\ &\times \sin^2\left(\frac{t}{2}\sqrt{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\right)\\ &- \cos^2\left(\frac{t}{2}\sqrt{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\phi_h|^2\eta^2}\right)\Bigg]\end{aligned} \tag{16}$$

From Eq. (15), the maximum gain is obtained when $|v|^2 = 1$ and $|u|^2 = 0$ which holds when $(\beta - \frac{\Omega_h}{2}) = 0$. Hence from Eq. (11), we get

$$t = \frac{(2m+1)\pi}{2\mathscr{G}|\phi_h|\Omega_h\eta(r)}; \quad m \in Z \tag{17}$$

The maximum average output power for the signal mode is given by

$$\mathscr{P}_{\text{Max}} = \frac{\int_0^t \dot{\mathscr{E}}_{gain}dt}{\int_0^t dt}\,. \tag{18}$$

Now from Eq. (16), we can have the rate of gain of ergotropy for $(\beta - \frac{\Omega_h}{2}) = 0$ as

$$\dot{\mathscr{E}}_{gain} = 2\hbar\nu\mathscr{G}\Omega_h|\phi_h|\eta(r)\sin\left(2\mathscr{G}\Omega_h|\phi_h|\eta(r)t\right)\,. \tag{19}$$

Now the maximum output power can be obtained from Eq. (18) as

$$\mathscr{P}_{\text{Max}} = \frac{4\hbar\nu\mathscr{G}\Omega_h|\phi_h|}{(2m+1)\pi f(r)}\,. \tag{20}$$

Figure 1[4] shows the maximum output power for both the direct coupling case $\mathscr{P}_{\text{Max}}$ and the momentum coupling case $\mathscr{P}^{M.C.}_{\text{Max}}$, as a function of radial distance r. It is evident from the plot that, in our set up, the signal mode is amplified more efficiently than in the case with direct coupling. This analysis is restricted to the $m = 0$ mode. The values of other parameters we have set are as follows; the radius of the mirror orbit $r_0 = 4r_s$, the mass of the black hole $M \sim 10^{30}$ kg, the atomic transition frequency $\Omega_h \sim 10^3$ Hz, the signal mode frequency $\nu \sim 10^4$ Hz, and the coupling constant $\mathscr{G} = 1$. We have used the values $G = 6.6743 \times 10^{-11}$ m^{3}kg^{-1}s^{-2}, $\hbar = 1.054 \times 10^{-34}$ kg $\cdot$ m^{2}s^{-1} and $c = 3 \times 10^8$ m $\cdot$ s^{-1}. It is important to note that as the mirror is placed at $r = 4r_s$, the output power drops sharply at this point.

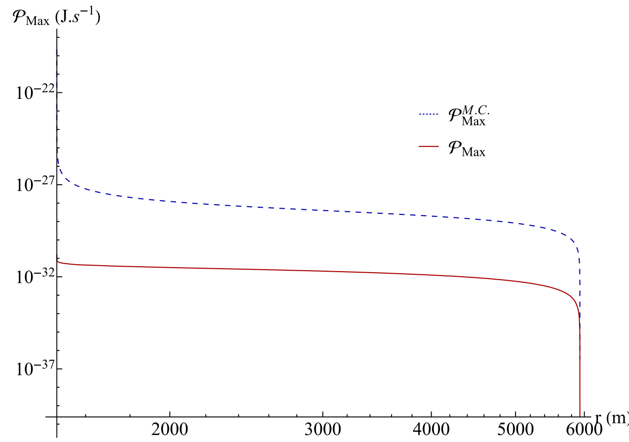

Fig. 1 Comparison between the maximum power output for the direct coupling and the momentum coupling case for the change in the radial distance r, where r is in the range $r_s \leq r \leq 4r_s$ with r_s denoting the Schwarzschild radius

In [15], the rate of change of ergotropy is proportional to the signal frequency and the flux of the redirected Hawking mode $|\phi_h(t, r_*)|$ which has the form obtained from Eq. (3)

$$|\phi_h(t, r_*)| = 2\sin\left[\frac{\Omega_h}{2}\left((r - r_0) + \ln\left(\frac{r-1}{r_0 - 1}\right)\right)\right]. \tag{21}$$

In our analysis, while considering the time derivative of the scalar field in the interaction Hamiltonian, the maximum output power is directly proportional to the frequency of the redirected Hawking radiation mode Ω_h along with the signal frequency ν. The lapse function of the black hole also dominates the efficiency of the signal mode as a result, we can observe a significant power boost very close to the event horizon of the black hole which was not observed in [15]. As per the discussion in [15], a significant boost in the power can be observed for $\mathscr{N}$ atoms which couples to the hot bath simultaneously and the total maximum output power will be given by [56] $\mathscr{P}^{M.C.}_{\text{Max}} \to \mathscr{N}\mathscr{P}^{M.C.}_{\text{Max}}$.

[3] $\mathscr{E}^{(f)}$ denotes the final ergotropy and $\mathscr{E}^{(i)}$ is the initial ergotropy.

[4] For the plot we have used the LogLogPlot to enhance the maximum power output for the standard coupling case.

3 Excitation of atoms by redirected hawking radiation examined by a detector with smearing

In this section we repeat the analysis for the cavity-attached detector having a smearing. The interaction between the two-level atoms and the redirected Hawking radiation is introduced by an interaction Hamiltonian. The form of the Hamiltonian for the detector with smearing can be written as

$$\hat{\mathscr{H}}_{int} = \mathscr{G}|e\rangle\langle g|\hat{b}_s^\dagger \hat{a}_h \int d\tilde{r}\, F(\tilde{r})\sqrt{-g}\, g^{00}\partial_0\phi_h(t, r_*) + H.C. \tag{22}$$

Here $F(r)$ is called the smearing function of the detector. It has a Gaussian like form as [57]

$$F(\tilde{r}) = \frac{e^{\frac{-(\tilde{r}-1)^2}{2L^2}}}{L\sqrt{2\pi}} \tag{23}$$

with L being the length of the detector. This smearing effect appears in a detector due to its physical size or the nature of its interacts with the incoming radiation.
As we have done in the previous section, we shall move to the interaction picture where the interaction Hamiltonian (Eq. (22)) takes the form as

$$\mathscr{H}_{int}^{(I)} = \begin{bmatrix} 0 & -\frac{i\hbar\mathscr{G}\Omega_h}{2}\mathscr{I}e^{-i(\beta-\frac{\Omega_h}{2})t} \\ \frac{i\hbar\mathscr{G}\Omega_h}{2}\mathscr{I}^* e^{i(\beta-\frac{\Omega_h}{2})t} & 0 \end{bmatrix} \tag{24}$$

where $\mathscr{I}$ is defined as

$$\mathscr{I} = \frac{1}{\sqrt{2\pi}L}\int dy \frac{(y+1)}{y} e^{-\frac{y^2}{2L^2}}\Big[e^{\frac{-i\Omega_h}{2}(y+1+\ln y)} - \mathscr{R}^* e^{\frac{i\Omega_h}{2}(y+1+\ln y)}\Big] \tag{25}$$

with $y = \tilde{r} - 1$ and $\mathscr{R} = e^{i\Omega_h(r_0+\ln(r_0-1))}$.
Now in a certain time t, the total system is represented by the state mentioned in Eq. (5). Initially, the atom is in its ground state $|g\rangle$ and the signal is in the Fock state $|n_s\rangle$. Hence initially the system is in the state $|\psi\rangle^{(i)} = |g, n_s, n_h\rangle$. Now the Hawking radiation mode redirected from the orbiting mirror is converted into a signal photon with frequency ν via the transition of two-level atoms from the ground state $|g\rangle$ to the excited state $|e\rangle$ due to the atom-field interaction. So the final state after interaction can be obtained by solving Schrödinger's equation. Solving the Eq. (8) using the Hamiltonian in Eq. (24), we get the relation between time dependent coefficients $u(t)$ and $v(t)$ as

$$\dot{u}(t) = -\mathscr{G}\Omega_h\mathscr{I}e^{-i(\beta-\frac{\Omega_h}{2})t}v(t)$$
$$\dot{v}(t) = \mathscr{G}\Omega_h\mathscr{I}^* e^{i(\beta-\frac{\Omega_h}{2})t}u(t)\,. \tag{26}$$

Initially $u(t=0) = 1$ and $v(t=0) = 0$. So, solving these equations along with the initial condition, we get the state of the total system after the interaction as

$$|\psi\rangle^{(f)} = \begin{pmatrix} e^{\frac{-it}{2}(\beta-\frac{\Omega_h}{2})}\Bigg[\cos\Big(\frac{t}{2}\sqrt{(\beta-\frac{\Omega_h}{2})^2+4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\Big) + \frac{i(\beta-\frac{\Omega_h}{2})\sin\Big(\frac{t}{2}\sqrt{(\beta-\frac{\Omega_h}{2})^2+4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\Big)}{\sqrt{(\beta-\frac{\Omega_h}{2})^2+4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}}\Bigg] \\ \frac{2\mathscr{G}\Omega_h|\mathscr{I}|}{\sqrt{(\beta-\frac{\Omega_h}{2})^2+4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}}\sin\Big(\frac{t}{2}\sqrt{(\beta-\frac{\Omega_h}{2})^2+4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\Big) \end{pmatrix}\begin{pmatrix}|1\rangle \\ |2\rangle\end{pmatrix}. \tag{27}$$

Now we shall calculate the ergotropy of the signal mode which is defined by the Hamiltonian $\mathscr{H}_s$ mentioned earlier in Eq. (13). Initially the signal is in $\rho_s^{(i)}$ state and hence the initial ergotropy can be obtained from Eq. (12) as

$$\mathscr{E}^{(i)} = Tr[|n_s\rangle\langle n_s|\hbar\nu\hat{b}_s^\dagger\hat{b}_s] - Tr[\hat{U}|n_s\rangle\langle n_s|\hat{U}^\dagger\hbar\nu\hat{b}_s^\dagger\hat{b}_s]$$
$$= \hbar\nu n_s\,. \tag{28}$$

Here the unitary operator transforms the states as $\hat{U}|n_s\rangle = |1\rangle$ and $\hat{U}|n_s+1\rangle = |0\rangle$. Now tracing out the Hawking radiation and the atom from the combined state in Eq. (14), the final state of the signal mode is $\rho_s^{(f)} = |u|^2|n_s\rangle\langle n_s| + |v|^2|n_s+1\rangle\langle n_s+1|$. So the final ergotropy of the signal mode is

$$\mathscr{E}^{(f)} = Tr[|u|^2|n_s\rangle\langle n_s|\hbar\nu\hat{b}_s^\dagger\hat{b}_s + |v|^2|n_s+1\rangle\langle n_s+1|\hbar\nu\hat{b}_s^\dagger\hat{b}_s]$$
$$- Tr[|u|^2|1\rangle\langle 1|\hbar\nu\hat{b}_s^\dagger\hat{b}_s + |v|^2|0\rangle\langle 0|\hbar\nu\hat{b}_s^\dagger\hat{b}_s]$$
$$= \hbar\nu\left((|u|^2+|v|^2)n_s + |v|^2 - |u|^2\right)$$
$$= \hbar\nu\left(n_s + (|v|^2 - |u|^2)\right)\,. \tag{29}$$

Here $|u|^2 + |v|^2 = 1$ is used. The gain in ergotropy of the signal mode is

$$\mathscr{E}_{gain} = \hbar\nu(|v|^2 - |u|^2)\,. \tag{30}$$

Now from Eq. (27), we have

$$|u|^2 = \cos^2\left(\frac{t}{2}\sqrt{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\right)$$

$$|v|^2 = \frac{4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2 - \left(\beta - \frac{\Omega_h}{2}\right)^2}{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}$$
$$\sin^2\left(\frac{t}{2}\sqrt{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\right). \quad (31)$$

Now substituting Eq. (31) into Eq. (30), we obtain the gain in energy between the initial and the final state as

$$\mathscr{E}_{gain} = \hbar\nu\Bigg[\frac{4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2 - \left(\beta - \frac{\Omega_h}{2}\right)^2}{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}$$
$$\times \sin^2\left(\frac{t}{2}\sqrt{(\beta - \frac{\Omega_h}{2})^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\right)$$
$$- \cos^2\left(\frac{t}{2}\sqrt{\left(\beta - \frac{\Omega_h}{2}\right)^2 + 4\mathscr{G}^2\Omega_h^2|\mathscr{I}|^2}\right)\Bigg]. \quad (32)$$

Now we aim to maximize the energy gain of the signal mode. From Eq. (30), the maximum gain will be obtained only if $|u|^2 = 0$ that means the atom is in excited state and this holds when the resonant transition $(\beta - \frac{\Omega_h}{2}) = 0$. Using these conditions, we get the interaction time $t = \frac{(2m+1)\pi}{2\mathscr{G}\Omega h|\mathscr{I}|}$. Now the maximum output power of the signal mode is

$$\mathscr{P}_{max} = \frac{\int_0^t \dot{\mathscr{E}}_{gain} dt}{\int_0^t dt}$$
$$= \frac{4\hbar\nu\mathscr{G}\Omega_h|\mathscr{I}|}{(2m+1)\pi} \quad (33)$$

where the analytical form of $\mathscr{I}$ is given in Eq. (25).

Figure 2 compares the maximum output power gain for a point-like detector $\mathscr{P}_{max}^{point}$ (Eq. (20)) and a detector with spatial smearing $\mathscr{P}_{max}^{smearing}$ (Eq. (33)). It is clearly seen from the plot that the spatial smearing enhances the output power compared to the point-like detector case. We have set the length of the detector to be $L = 0.001r_s$, with r_s being the Schwarzschild radius.

In this case, the maximum output power is directly proportional to the frequency of the signal mode and the redirected Hawking mode.

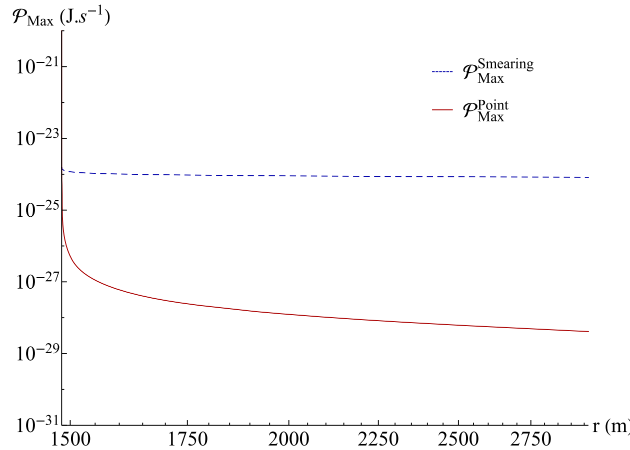

Fig. 2 Comparison between the maximum power output for the point like detector and the detector with smearing case

4 Conclusion

We consider the thought experiment in which a two-level atom freely falls into the gravitational field of a non-rotating, static, and spherically symmetric black hole through a cavity, with the detector attached to it. The Hawking radiation redirected from an orbiting mirror acts as the source of amplification of the light quanta. The mirror converts the outgoing Hawking radiation into ingoing Rindler modes and enhances the interaction process. As a result, the signal photons become amplified, with the redirected Hawking radiation providing the required energy. The amplification of the signal depends on several factors: it is proportional to the frequency of the signal mode as well as to the frequency of the redirected Hawking mode, and it also depends on the flux associated with the ingoing Rindler mode ϕ_h.

From the discussion in [15], it is an important result that black hole gravity can play a crucial role in coherent light amplification. In [15], the atom–field interaction was taken to be

$$\mathscr{H}_{\rm int} = \mathscr{G}|e\rangle\langle g|\hat{b}_s^\dagger \hat{a}_h \phi_h(t, r_*) + H.C. \quad (34)$$

for which the amplification is governed solely by the frequency of the signal mode, together with the flux of the Hawking radiation. In the present work, we consider the momentum coupling case when the detector is point-like as well as when the detector has spatial smearing. Our analysis reveals an additional and qualitatively new feature: in these cases, the amplification is not only controlled by the mode frequencies and the Hawking flux, but is also explicitly enhanced by the black hole spacetime itself through its dependence on the lapse function.

There is a strong theoretical basis for the fact that the Hawking radiation is responsible for the proposed effect.

If the Hawking radiation got shielded before emitting from the event horizon of the black hole, then the fields will be unchanged by the orbiting mirror and that assures the Rindler vacuum. Hence there will be no generated photons since the mirror accelerating in Minkowski vacuum, only can generate the photons [58,59]. Hence the excitation of atoms can only be initiated if the redirected Hawking radiation interacts with them. As can also be observed from Fig. 1, the momentum coupling case has significant power boost compared to the standard coupling case in [15], especially near the event horizon of the black hole because of the dependence of the maximum power output on the inverse of the lapse function. This a very important result in our work.

Next, we explored the effect examined by a detector with smearing. This smearing in detector arises due to its size and nature of interaction with the radiation. In Fig. 2, it is observed that the presence of spatial smearing of the detector, enhances the maximum output power compared to the point-like detector case. We find out that the output power of the signal mode is related to this smearing function, the frequency of the Hawking radiation, and the frequency of the signal mode.

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