Published by Institute of Physics Publishing for SISSA

Received: *February 5, 2007*
Accepted: *March 27, 2007*
Published: *April 4, 2007*

Interaction of Hawking radiation with static atoms outside a Schwarzschild black hole

Wenting Zhou and Hongwei Yu*

Department of Physics and Institute of Physics,
Hunan Normal University, Changsha, Hunan 410081, China
E-mail: wt-zhou@163.com, hwyu@hunnu.edu.cn

Abstract: We study the spontaneous excitation of static two-level atoms interacting with Hawking radiation of a massless scalar field in the Hartle-Hawking vacuum outside a four-dimensional Schwarzschild black hole, and calculated the contributions of the vacuum fluctuations and radiation reaction to the rate of change of the mean atomic energy. We show that an atom held static outside the Schwarzschild black hole spontaneously excites as if it were in a thermal bath of radiation at a proper temperature which reduces to the temperature of Hawking radiation in the spatial asymptotic region. Our discussion, therefore, establishes an interesting relationship between the existence of Hawking radiation and the spontaneous excitation of a static two-level atom in vacuum in the exterior of a black hole.

Keywords: Black Holes, Models of Quantum Gravity.

*Corresponding author

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1. Introduction

Recently, there has been a great deal of interest in the radiative properties of uniformly accelerated atoms in the Minkowski vacuum [1 − 9] and the spontaneous excitation of these atoms interacting with fluctuating vacuum scalar [1, 4 − 6] and electromagnetic fields [7 − 9] has been extensively studied. These investigations employ a formalism based upon that proposed by Dalibard, Dupont-Roc and Cohen-Tannoudji(DDC) [10, 11] which distinctively separates the contributions of vacuum fluctuations and radiation reaction to the rate of change of an atomic observable by demanding a symmetric operator ordering of atom and field variables in a Heisenberg picture approach to the problem, and show that when an atom is accelerated, the delicate balance between vacuum fluctuations and radiation reaction that ensures the ground state atom's stability in vacuum is altered, making possible the transitions to excited states for ground-state atoms even in vacuum. As a result, the accelerated atoms spontaneously excite in vacuum as if immersed in a thermal bath at the Fulling-Davies-Unruh (FDU) temperature [12]. This phenomenon serves to provide a physically appealing interpretation of the FDU effect [12], since it gives a transparent illustration for why an accelerated detector clicks (See ref. [13] for a discussion in a different context and ref. [14] for a non-perturbative approach to study the interaction of a uniformly accelerated detector, modelled by a harmonic oscillator which may be regarded as a simple version of an atom, with a quantum field in (3+1) dimensional spacetime).

On the other hand, it is well-known that the FDU effect associated with uniformly accelerated observers is closely related to the Hawking radiation of black holes. Therefore, one may wonder what happens if an atom is held static outside a black hole. Using an equivalence principle-type argument, i.e., the same accelerated atom is seen by comoving observers as a static one in a uniform "gravitational field", one may expect that atoms held static outside a black hole would also spontaneously excite. Furthermore, if spontaneous excitation does occur, will the excitation rate be consistent with what one expects assuming the existence of the Hawking radiation? This is the issue we plane to address in this paper. We shall calculate, using the formalism developed in refs. [1, 10, 11], the spontaneous excitation rate of a static two-level atom interacting with a massless scalar field in the Hartle-Hawking vacuum outside a Schwarzschild black hole and show that the atom spontaneously excites as if in a thermal bath of Hawking radiation.

2. General formalism

Let us consider a two-level atom in interaction with a quantum real massless scalar field outside a Schwarzschild black hole. The metric of the spacetime can be written in terms of Schwarzschild coordinates as

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right) , \tag{2.1}$$

where M is the mass of the black hole. Without loss of generality, we assume a pointlike two-level atom on a stationary space-time trajectory $x(\tau)$, where τ denotes the proper time on the trajectory. The stationarity of the trajectory guarantees the existence of stationary atomic states, $|+\rangle$ and $|-\rangle$, with energies $\pm 1/2\omega_0$ and a level spacing ω_0. The atom's Hamiltonian which controls the time evolution with respect to τ is given, in Dicke's notation [15], by

$$H_A(\tau) = \omega_0 R_3(\tau) , \tag{2.2}$$

where $R_3 = 12|+\rangle\langle+| - 12|-\rangle\langle-|$ is the pseudospin operator commonly used in the description of two-level atoms [15]. The free Hamiltonian of the quantum scalar field that governs its time evolution with respect to τ is

$$H_F(\tau) = \int d^3k \, \omega_{\vec{k}} \, a^{\dagger}_{\vec{k}} a_{\vec{k}} \, dt d\tau . \tag{2.3}$$

Here $a^{\dagger}_{\vec{k}}$, $a_{\vec{k}}$ are the creation and annihilation operators with momentum $\vec{k}$. Following ref. [1], we assume that the interaction between the atom and the quantum field is described by a Hamiltonian

$$H_I(\tau) = \mu \; R_2(\tau) \, \phi(x(\tau)) , \tag{2.4}$$

where μ is a coupling constant which we assume to be small, $R_2 = 12i(R_- - R_+)$, and $R_+ = |+\rangle\langle-|$, $R_- = |-\rangle\langle+|$. The coupling is effective only on the trajectory $x(\tau)$ of the atom.

We can now write down the Heisenberg equations of motion for the atom and field observables. The field is always considered to be in its vacuum state $|0\rangle$. We will separately discuss the two physical mechanisms that contribute to the rate of change of atomic observables: the contribution of vacuum fluctuations and that of radiation reaction. For this purpose, we can split the solution of field ϕ of the Heisenberg equations into two parts: a free or vacuum part ϕ^f, which is present even in the absence of coupling, and a source part ϕ^s, which represents the field generated by the interaction between the atom and the field. Following DDC [10, 11], we choose a symmetric ordering between atom and field variables and consider the effects of ϕ^f and ϕ^s separately in the Heisenberg equations of an arbitrary atomic observable G. Then, we obtain the individual contributions of vacuum fluctuations and radiation reaction to the rate of change of G. Since we are interested in the spontaneous emission of the atom, we will concentrate on the mean atomic excitation energy $\langle H_A(\tau)\rangle$. The contributions of vacuum fluctuations(vf) and radiation reaction(rr) to the rate of change of $\langle H_A\rangle$ can be written as (cf. ref. [10, 11, 1])

$$\langle dH_A(\tau)d\tau\rangle_{\rm vf} = 2i\,\mu^2 \int_{\tau_0}^{\tau} d\tau'\, C^F(x(\tau),x(\tau'))dd\tau\chi^A(\tau,\tau') \ , \tag{2.5}$$

$$\langle dH_A(\tau)d\tau\rangle_{rr} = 2i\,\mu^2 \int_{\tau_0}^{\tau} d\tau'\, \chi^F(x(\tau),x(\tau'))dd\tau C^A(\tau,\tau') \ , \tag{2.6}$$

with $|\rangle = |a,0\rangle$ representing the atom in the state $|a\rangle$ and the field in the vacuum state $|0\rangle$. Here the statistical functions of the atom, $C^A(\tau,\tau')$ and $\chi^A(\tau,\tau')$, are defined as

$$C^A(\tau,\tau') = 12\langle a|\{R_2^f(\tau),R_2^f(\tau')\}|a\rangle \ , \tag{2.7}$$

$$\chi^A(\tau,\tau') = 12\langle a|[R_2^f(\tau),R_2^f(\tau')]|a\rangle \ , \tag{2.8}$$

and those of the field are as

$$C^F(x(\tau),x(\tau')) = 12\langle 0|\{\phi^f(x(\tau)),\phi^f(x(\tau'))\}|0\rangle \ , \tag{2.9}$$

$$\chi^F(x(\tau),x(\tau')) = 12\langle 0|[\phi^f(x(\tau)),\phi^f(x(\tau'))]|0\rangle \ . \tag{2.10}$$

C^A is called the symmetric correlation function of the atom in the state $|a\rangle$, χ^A its linear susceptibility. C^F and χ^F are the Hadamard function and Pauli-Jordan or Schwinger function of the field respectively. The explicit forms of the statistical functions of the atom are given by

$$C^A(\tau,\tau') = 12\sum_b |\langle a|R_2^f(0)|b\rangle|^2 \left(e^{i\omega_{ab}(\tau-\tau')} + e^{-i\omega_{ab}(\tau-\tau')}\right) \ , \tag{2.11}$$

$$\chi^A(\tau,\tau') = 12\sum_b |\langle a|R_2^f(0)|b\rangle|^2 \left(e^{i\omega_{ab}(\tau-\tau')} - e^{-i\omega_{ab}(\tau-\tau')}\right) \ , \tag{2.12}$$

where $\omega_{ab} = \omega_a - \omega_b$ and the sum runs over a complete set of atomic states.

3. Spontaneous excitation of static atoms outside a black hole.

Let us note that, in the exterior region of the Schwarzschild black hole, a complete set of normalized basis functions for the massless scalar field that satisfy the Klein-Gordon equation is given by

$$\overrightarrow{u}_{\omega lm} = (4\pi\omega)^{-\frac{1}{2}} e^{-i\omega t}\overrightarrow{R}_l(\omega|r)Y_{lm}(\theta,\varphi) \ , \tag{3.1}$$

$$\overleftarrow{u}_{\omega lm} = (4\pi\omega)^{-\frac{1}{2}} e^{-i\omega t}\overleftarrow{R}_l(\omega|r)Y_{lm}(\theta,\varphi) \ , \tag{3.2}$$

where $Y_{lm}(\theta,\varphi)$ are the spherical harmonics and the radial functions have the following asymptotic forms [16]

$$\overrightarrow{R}_l(\omega|r) \sim \begin{cases} r^{-1}e^{i\omega r_*} + \overrightarrow{A}_l(\omega)r^{-1}e^{-i\omega r_*}, & r\to 2M \ , \\ B_l(\omega)r^{-1}e^{i\omega r_*}, & r\to\infty \ , \end{cases} \tag{3.3}$$

$$\overleftarrow{R}_l(\omega|r) \sim \begin{cases} B_l(\omega)r^{-1}e^{-i\omega r_*}, & r\to 2M \ , \\ r^{-1}e^{-i\omega r_*} + \overleftarrow{A}_l(\omega)r^{-1}e^{i\omega r_*}, & r\to\infty \ , \end{cases} \tag{3.4}$$

with

$$r_* = r + 2M \ln\left(\frac{r}{2M} - 1\right), \tag{3.5}$$

being the Regge-Wheeler tortoise coordinate. The physical interpretation of these modes is that $\overrightarrow{u}$ represents modes emerging from the past horizon and the $\overleftarrow{u}$ denotes those coming in from infinity.

We now apply formalism outlined in the preceding section to the case of the Hartle-Hawking vacuum. The Hartle-Hawking vacuum is defined by taking incoming modes to be positive frequency with respect to the Kruskal coordinate V and the outgoing modes to be positive frequency with respect to the Kruskal coordinate U. One can show that the Wightman function for massless scalar fields in the Hartle-Hawking vacuum is given by [17, 18]

$$\begin{aligned} D_H^+(x,x') \; &= \frac{1}{4\pi}\sum_{lm} |Y_{lm}(\theta,\varphi)|^2 \times \\ &\times \int_{-\infty}^{+\infty} \frac{d\omega}{\omega}\left[\frac{e^{-i\omega\Delta t}}{1-e^{-2\pi\,\omega/\kappa}}\,|\overrightarrow{R}_l(\omega|r)|^2 + \frac{e^{-i\omega\Delta t}}{1-e^{-2\pi\,\omega/\kappa}}\,|\overleftarrow{R}_l(\omega|r)|^2\right], \end{aligned} \tag{3.6}$$

where $\kappa = 1/4M$ is the surface gravity of the black hole. Then the statistical functions of the scalar field in the Hartle-Hawking vacuum readily follows

$$\begin{aligned} C^F(x(\tau), x(\tau')) = \frac{1}{8\pi}\sum_{lm} |Y_{lm}(\theta,\varphi)|^2 \int_{-\infty}^{+\infty} \frac{d\omega}{\omega}\left(e^{\frac{i\omega\Delta\tau}{\sqrt{1-2M/r}}} + e^{-\frac{i\omega\Delta\tau}{\sqrt{1-2M/r}}}\right) \\ \times\left(\frac{|\overrightarrow{R}_l(\omega|r)|^2}{1-e^{-2\pi\,\omega/\kappa}} + \frac{|\overleftarrow{R}_l(\omega|r)|^2}{e^{2\pi\,\omega/\kappa}-1}\right), \end{aligned} \tag{3.7}$$

and

$$\begin{aligned} \chi^F(x(\tau), x(\tau')) = \frac{1}{8\pi}\sum_{lm} |Y_{lm}(\theta,\varphi)|^2 \int_{-\infty}^{+\infty} \frac{d\omega}{\omega}\left(e^{\frac{i\omega\Delta\tau}{\sqrt{1-2M/r}}} - e^{-\frac{i\omega\Delta\tau}{\sqrt{1-2M/r}}}\right) \\ \times\left(\frac{|\overleftarrow{R}_l(\omega|r)|^2}{e^{2\pi\,\omega/\kappa}-1} - \frac{|\overrightarrow{R}_l(\omega|r)|^2}{1-e^{-2\pi\,\omega/\kappa}}\right). \end{aligned} \tag{3.8}$$

where use has been made of

$$\Delta\tau = \Delta\, t\sqrt{1-\frac{2M}{r}}\,. \tag{3.9}$$

Plugging the above results into eq. (2.5) and performing the double integration, we obtain the contribution of the vacuum fluctuations to the rate of change of the mean atomic energy for an atom held static at a distance r from the black hole

$$\begin{aligned}
\left\langle \frac{dH_A(\tau)}{d\tau} \right\rangle_{\rm vf} = -\frac{\mu^2}{4\pi} \Bigg\{ & \sum_{\omega_a>\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2 \Bigg[\frac{P(-\,\omega_{ab},r)}{e^{(2\pi\,\omega_{ab})/\kappa_r}-1} \\
& \qquad + \left(1+\frac{1}{e^{(2\pi\,\omega_{ab})/\kappa_r}-1}\right) P(\omega_{ab},r) \Bigg] \\
& - \sum_{\omega_a<\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2 \Bigg[\frac{P\,(\omega_{ab},r)}{e^{(2\pi\,|\,\omega_{ab}|)/\kappa_r}-1} \\
& \qquad + \left(1+\frac{1}{e^{(2\pi\,|\,\omega_{ab}|)/\kappa_r}-1}\right) P\,(-\,\omega_{ab},r) \Bigg] \Bigg\} \,.
\end{aligned} \tag{3.10}$$

Here we have defined

$$\kappa_r = \frac{\kappa}{\sqrt{1-\frac{2M}{r}}}\,, \tag{3.11}$$

$$\begin{aligned}
P\,(\omega_{ab}\,,r) &= \frac{\pi}{\omega_{ab}^2} \sum_{lm} |Y_{lm}(\theta,\varphi)|^2 \left[\left| \overrightarrow{R}_l\left(\omega_{ab}\, r\sqrt{1-\frac{2M}{r}}\right)\right|^2 + \left| \overleftarrow{R}_l\left(-\omega_{ab}\, r\sqrt{1-\frac{2M}{r}}\right)\right|^2 \right] \\
&= \frac{1}{\omega_{ab}^2} \sum_{l} \frac{2l+1}{4} \left[\left| \overrightarrow{R}_l\left(\omega_{ab}\, r\sqrt{1-\frac{2M}{r}}\right)\right|^2 + \left| \overleftarrow{R}_l\left(-\omega_{ab}\, r\sqrt{1-\frac{2M}{r}}\right)\right|^2 \right],
\end{aligned} \tag{3.12}$$

and have extended the integration range for τ to infinity for sufficiently long times $\tau-\tau_0$. Notice that in the second line in eq. (3.12), we have also appealed to the following property of the spherical harmonics

$$\sum_{m=-l}^{l} |\, Y_{lm}(\,\theta,\varphi\,)\,|^2 = \frac{2l+1}{4\pi}\,. \tag{3.13}$$

Similarly, one finds the contribution of radiation reaction by use of eq. (2.6)

$$\begin{aligned}
\left\langle \frac{dH_A(\tau)}{d\tau} \right\rangle_{rr} = -\frac{\mu^2}{4\pi} \Bigg\{ & \sum_{\omega_a>\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2 \Bigg[-\frac{P(-\,\omega_{ab},r)}{e^{(2\pi\,\omega_{ab})/\kappa_r}-1} \\
& \qquad + \left(1+\frac{1}{e^{(2\pi\,\omega_{ab})/\kappa_r}-1}\right) P(\omega_{ab},r) \Bigg] \\
& - \sum_{\omega_a<\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2 \Bigg[\frac{P\,(\omega_{ab},r)}{e^{(2\pi\,|\,\omega_{ab}|)/\kappa_r}-1} \\
& \qquad - \left(1+\frac{1}{e^{(2\pi\,|\,\omega_{ab}|)/\kappa_r}-1}\right) P\,(-\,\omega_{ab},r) \Bigg] \Bigg\} \,.
\end{aligned} \tag{3.14}$$

Adding up two contributions, we obtain the total rate of change of the mean atomic energy

$$\begin{aligned}
\left\langle \frac{dH_A(\tau)}{d\tau} \right\rangle_{\rm tot} = -\frac{\mu^2}{2\pi} \Bigg[& \sum_{\omega_a>\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2\, P\,(\omega_{ab},r) \left(1+\frac{1}{e^{(2\pi\,\omega_{ab})/\kappa_r}-1}\right) \\
& - \sum_{\omega_a<\omega_b} \omega_{ab}^2\, |\langle a|R_2^f(0)|b\rangle|^2\, P(\omega_{ab},r)\, \frac{1}{e^{(2\pi\,|\,\omega_{ab}|)/\kappa_r}-1} \Bigg] \,.
\end{aligned} \tag{3.15}$$

Now one can see that, for a ground state atom held static at a radial distance r from the black hole, the delicate balance between the vacuum fluctuations and radiation reaction that ensures stability of ground state atoms in vacuum in flat spacetimes no longer exists. There is a positive contribution from the second term ($\omega_a < \omega_b$ term), thus transitions from ground state to the excited states can occur spontaneously in the exterior region of the black hole. Except for a factor $P(\omega_{ab}, r)$, which may be envisaged as a result of backscattering of the field modes off the spacetime curvature, the spontaneous excitation rate is what one would obtain if the atom were immersed in a thermal bath of radiation at the temperature

$$T = \frac{\kappa_r}{2\pi} = \frac{\kappa}{2\pi} \frac{1}{\sqrt{1-\frac{2M}{R}}} = (g_{00})^{-1/2}\, T_H \ , \tag{3.16}$$

where $T_H = \kappa/2\pi$ is the Hawking temperature of the black hole. This is actually the well-known Tolman relation [19] which gives the proper temperature as measured by a local observer. Let us note that the appearance of the factor, $P(\omega_{ab}, r)$, in the rate of the change of the mean atomic energy, modifies the frequency response of the atom's emission and absorption in the thermal bath of radiation. Similar modification also occurs for the uniformly accelerated atoms in the flat spacetime with boundaries [4], where the modification is caused by the presence of a reflecting boundary as opposed to the backscattering off the spacetime curvature here. Using the following asymptotic properties of the radial functions

$$\sum_{l=0}^{\infty}(2l+1)\,|\overrightarrow{R}_l(\omega\,|r\,)\,|^2 \sim \begin{cases} \dfrac{4\omega^2}{1-\frac{2M}{r}} \ , & r \to 2M \ , \\ \dfrac{1}{r^2}\displaystyle\sum_{l=0}^{\infty}(2l+1)\,|\,B_l\,(\omega)\,|^2 \ , & r \to \infty \ , \end{cases} \tag{3.17}$$

$$\sum_{l=0}^{\infty}(2l+1)\,|\overleftarrow{R}_l(\omega\,|r\,)\,|^2 \sim \begin{cases} \dfrac{1}{4M^2}\displaystyle\sum_{l=0}^{\infty}(2l+1)\,|\,B_l\,(\omega)\,|^2, & r \to 2M \ , \\ 4\omega^2, & r \to \infty \ , \end{cases} \tag{3.18}$$

one can obtain

$$P(\omega_{ab}, r) \sim \begin{cases} 1 + \dfrac{1}{16M^2\omega_{ab}^2}\displaystyle\sum_{l=0}^{\infty}(2l+1)\,|\,B_l\,(\,0\,)\,|^2 \ , & r \to 2M \ , \\ 1 + \dfrac{1}{4r^2\omega_{ab}^2}\displaystyle\sum_{l=0}^{\infty}(2l+1)\,|\,B_l\,(\,\omega_{ab})\,|^2 \ , & r \to \infty \ , \end{cases} \tag{3.19}$$

For an atom at spatial infinity ($r \to \infty$), $P(\omega_{ab}, r) \to 1$, and the temperature as perceived by the atom, T, approaches T_H. Therefore, an static atom in the spatial asymptotic region outside the black hole would spontaneously excite as if in a thermal bath of radiation at the Hawking temperature. This is consistent with our common understanding that the Hartle-Hawking vacuum corresponds to a black hole in equilibrium with an infinite sea of black-body radiation. However, as the atom approaches the horizon ($R \to 2M$), the proper temperature T as perceived by a local atom diverges. This can be attributed to the fact that the atom must be in acceleration relative to the local free-falling frame to maintain at a fixed distance from the black hole, and this acceleration, which blows up at the horizon, gives rises to additional thermal effect [12].

4. Summary

We have investigated the spontaneous excitation of a static two-level atom outside a Schwarzschild black hole which is in interaction with a massless scalar field in the Hartle-Hawking vacuum, and calculated the contributions of the vacuum fluctuations and radiation reaction to the rate of change of the mean atomic energy. Our results show that a static atom outside a Schwarzschild black hole spontaneously excites as if it were in a thermal bath of radiation at a proper temperature which reduces to the temperature of Hawking radiation in the spatial asymptotic region, except for a frequency response distortion caused by the backscattering of the field modes off the spacetime curvature. Therefore, an interesting relationship is established, in this paper, between the existence of Hawking radiation and the spontaneous excitation of a static two-level atom in vacuum in the exterior of a black hole.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant No.10575035, and the Program for New Century Excellent Talents in University (NCET, No. 04-0784), the Key Project of Chinese Ministry of Education (No. 205110), and the National Basic Research Program of China under Grant No. 2003CB71630.

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JHEP04(2007)024