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The black hole quantum atmosphere

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ABSTRACT

Ever since the discovery of black hole evaporation, the region of origin of the radiated quanta has been a topic of debate. Recently it was argued by Giddings that the Hawking quanta originate from a region well outside the black hole horizon by calculating the effective radius of a radiating body via the Stefan–Boltzmann law. In this paper we try to further explore this issue and end up corroborating this claim, using both a heuristic argument and a detailed study of the stress energy tensor. We show that the Hawking quanta originate from what might be called a quantum atmosphere around the black hole with energy density and fluxes of particles peaked at about $4MG$, running contrary to the popular belief that these originate from the ultra high energy excitations very close to the horizon. This long distance origin of Hawking radiation could have a profound impact on our understanding of the information and transplanckian problems.

1. Introduction

The discovery of Hawking radiation [1] changed our perspective towards black holes, giving us a deeper insight about the microscopic nature of gravity. At the same time, within the semi-classical framework, the current understanding of such process still leaves open several issues. Of course, a well known unresolved problem of black hole physics is the information loss paradox [2–4], i.e. the apparent incompatibility between the complete thermal evaporation of a black hole endowed with an event horizon and unitary evolution as prescribed by quantum mechanics.

For restoring unitarity of Hawking radiation and addressing the information loss problem correctly, it is important (among other things) to know from where the Hawking quanta originate. For example, if one assumes a near horizon origin of the Hawking radiation, then one way to restore unitarity is by conjecturing some sort of UV-dependent entanglement between partner Hawking quanta which would enable the late time Hawking flux to retrieve the information in the early stages of the evaporation process. Such scenario seems to lead to the so called "firewall" argument as the conjectured lack of maximal entanglement between the Hawking pairs makes the near horizon state singular and eventually demands some drastic modification of the near horizon geometry [5]. On the other hand, if one believes in a longer distance origin of the Hawking quanta, some effect must be operational at a larger scale for restoring unitarity rather than near the horizon, avoiding the "firewall".

A similar open issue is the transplanckian origin of Hawking quanta. Hawking's original calculation indicates that the quanta originate near the black hole horizon in a highly blue-shifted state requiring an assumption on the UV completion of the effective field theory used for the computation and on the lack of back-reaction on the underlying geometry.[1] While it was debated for a while if Hawking quanta could originate initially, during the star collapse, and later released over a very long time, it was convincingly argued in [8] that this cannot be the case if an event horizon indeed forms. This leads to the conclusion that the Hawking quanta are generated in a region outside the horizon. A conclusion corroborated by studies of the Hawking modes correlation structure where it was shown that mode conversion happens over a long distance from the horizon [9]. A more recent claim in this direction, based on calculating the size of the radiating body via the Stefan–Boltzmann law, showed that the Hawking quanta originate in a near horizon quantum region, a sort of black hole "*atmosphere*" [10]. It is a well known fact that the typical wavelength of the radiated quanta is comparable to the size of the black hole,

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[1] See, for instance, Refs. [6,7] for a black hole evaporation analysis where these issues can be addressed in a quantum gravity context.

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so one might think that the point particle description is not very accurate. However, as measured by a local observer near the horizon, the wavelength is highly blue-shifted when traced back from infinity to the horizon, thus validating the point particle description.

The Hawking process can be explained heuristically as-well, for example via a tunneling mechanism where the particle tunnels out of the horizon or the anti particle (propagating backwards in time) tunnels into the horizon and as a result of this we get the constant Hawking flux at infinity [11]. Alternatively, one popular picture is to imagine that the strong tidal force near the black hole horizon stops the annihilation of the particle and anti-particle pairs that are formed spontaneously from the vacuum. Once the antiparticle is "hidden" within the black hole horizon, having a negative energy effectively, the other particle can materialize and escape to infinity [12,13].

In this paper we shall explicitly make use of this latter heuristic picture as well as of a full calculation of the stress energy tensor in $1+1$ dimensions. We shall see that both methods seem to agree in suggesting that the Hawking quanta originate from the black hole *atmosphere* and not from a region very close to the horizon. In section 2, based on the heuristic picture of Hawking radiation described above and invoking the uncertainty principle and tidal forces, we show that most of the contribution to the radiation spectrum comes from a region far away from the horizon. In section 3 we further strengthen our claim by a detailed calculation of the renormalized stress energy tensor, which indicates a similar result.

2. A gravitational Schwinger effect argument

One ingredient of our heuristic argument to identify a quantum atmosphere outside the black hole horizon, where particle creation takes place, is the uncertainty principle. However, the use of the uncertainty principle alone, as originally suggested by Parker [14], does not contain any physically relevant information about the location of particle production and why smaller black holes should be hotter. Indeed, the uncertainty principle in this case provides a rough estimate of the region of particle production as inversely proportional to the energy of the Hawking quanta when they are produced, but it does not take into account any dynamical mechanism to estimate the probability of spontaneous emission.

Thus one can improve this argument by invoking a physical process of creation of the Hawking quanta and using the uncertainty principle as a complementary tool to estimate the region of origin of the quanta. In this section, we try to achieve this goal by relying on tidal forces.

Let us then consider a situation where a virtual pair, consisting of a particle and anti-particle, pops out of the vacuum spontaneously for a very short time interval and then annihilates itself. In the Schwinger effect [15] a static electric field is assumed to act on a virtual electron–positron pair until the two partners are torn apart once the threshold energy necessary to become a real electron–positron pair is provided by the field. Energy is conserved due to the fact that the electric potential energy has opposite sign for partners with opposite charge. However, in its gravitational counterpart a priori only vacuum polarization can be induced by a static field in the absence of an horizon.

In fact, only in the presence of the latter one has both the characteristic peeling structure of geodesics (diverging away from the horizon on both its sides) as well as the presence of an ergoregion behind it.[2] The presence of an ergoregion is crucial for energy conservation as it allows for negative energy states given that in it the norm of the timelike Killing vector, with respect to which we compute energy, changes sign.

Indeed, if a Schwinger-like process takes place near the black hole horizon, due to the tidal force of the black hole and the peeling of geodesics, the pair can get spatially separated and one partner can enter the black hole horizon following a timelike or null curve with negative energy while the other particle can escape to infinity and contribute to the Hawking flux. In this picture, we are implicitly assuming that virtual particles in the vicinity of a black hole horizon move along geodesics when they are just about to go on-shell.

Therefore, the physical scenario we want to envisage is that of a particle–antiparticle pair pulled apart by the black hole tidal force outside the horizon until they go on-shell as one of them reaches the horizon[3] located at $r_s = 2GM/c^2$ (actually an infinitesimal distance inside it so that the geodesic motion will drag it further inside) while the other particle is at a radial coordinate distance $r = r_*$. Once on-shell, the outgoing particle eventually reaches infinity and contributes to the Hawking spectrum. In order to do so though, it has to be created with an energy corresponding to the energy of the Hawking quanta at a distance $r_* > r_s$ from the center of the black hole as measured by a local static observer; this can be reconstructed by noticing that

$$\omega_r = \frac{\omega_\infty}{\sqrt{g_{00}}}, \tag{1}$$

where ω_∞ is the energy at infinity and we are using the $(+,-,-,-)$ signature. At infinity, the thermal spectrum of Hawking radiation gives

$$\omega_\infty = \gamma \frac{k_B T_H}{\hbar}, \tag{2}$$

where the Hawking temperature for a black hole of mass M reads $k_B T_H = \frac{\hbar c^3}{8\pi GM}$, and γ is a numerical factor spanning the energy range of the quanta giving rise to the radiation thermal spectrum. At the peak of the spectrum $\gamma \approx 2.82$.

Thus, we get

$$\omega_\infty = \gamma \frac{c^3}{8\pi GM} \tag{3}$$

and

$$\omega_r = \gamma \frac{c}{4\pi r_s} \frac{1}{\sqrt{1-\frac{r_s}{r}}}. \tag{4}$$

This energy is provided by the work done by the gravitational field to pull the two partners apart. We can compute this work in the static frame outside a black hole and compare it with $\omega(r_*)$. Using this relation, we can determine the region from which the Hawking quanta originate. This is the process we now want to implement. Although in the rest of this Section we present the detailed derivation of the relation between the outgoing particle energy and the radial distance at which it goes on-shell for the massive case, our result holds also for massless particles. We comment at the end of this Section on how the same Schwinger effect

[2] This is strictly true only for non-rotating black holes, for rotating ones the ergoregion lies outside of the horizon allowing for the classical phenomenon of superradiance. However, the quantum emission still requires the peculiar peeling structure of geodesics typical of the horizon.

[3] One could also consider the case where the ingoing particle tunnels through the horizon and goes on-shell well inside the horizon (as e.g. suggested by the results of [9]); however, since in our analysis below we are interested in the tidal force as computed in the outgoing particle rest frame, this should not affect the final expression for the force. Thus, from the point of view of an outside static observer, the work done by the gravitational field on the pair (in our heuristic derivation) is insensitive to the exact location where the ingoing particle becomes real.