Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 28, 2016, Sofia

HORIZON OSCILLATIONS FOR PRESERVING THE EQUIVALENCE PRINCIPLE

Alexander Yosifov, Lachezar Filipov[1]

[1]Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: alexander_yosifov@abv.bg, lfilipov@space.bas.bg

Abstract
We present a generic phenomenon which provides a set of boundary conditions for preservation of the effective field theory after Page time. We further argue the proposed scenario can account for the physical membrane in the complementarity conjecture as far as an outside observer at future null infinity is concerned.

Introduction

Recently, it has been argued by AMPS [1] there is an inconsistency between the postulates of black hole complementarity [2] which causes drama for an infalling observer after half of the mass has been evaporated. The three postulates are given as follows. The absence of drama for an infalling observer is also mentioned in [2], and has been established in the literature as a fourth postulate.

Postulate 1: The process of formation and evaporation of a black hole, as viewed by a distant observer, can be described entirely within the context of standard quantum theory. In particular, there exists a unitary S‒matrix which describes the evolution from infalling matter to outgoing Hawking-like radiation.

Postulate 2: Outside the stretched horizon of a massive black hole, physics can be described to good approximation by a set of semiclassical field equations.

Postulate 3: To a distant observer, a black hole appears to be a quantum system with discrete energy levels. The dimension of the subspace of states describing a black hole of mass M is the exponential of the Bekenstein entropy $S(M)$.

Postulate 4: A freely falling observer experiences nothing out of the ordinary when crossing the horizon.

We wish to preserve unitarity in accordance with Postulate 1

(1) $\rho=|\psi\rangle\langle\psi|$

Following the semiclassical approximation, stated in Postulate 2, combined with the desired information preservation in Postulate 1, we see that an infalling observer should encounter high-energy quanta at the horizon, Fig. 1.

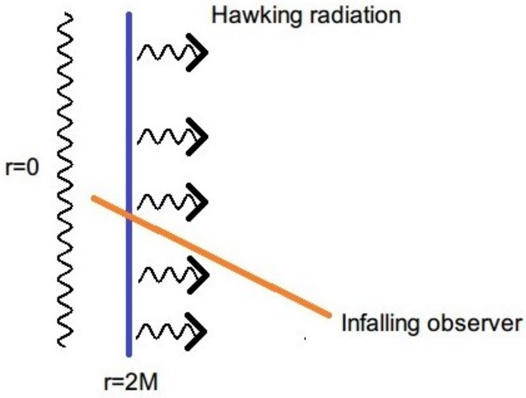

Fig. 1. Black hole in Eddington-Finkelstein coordinates. The wave-like line (r=0) is the singularity. The event horizon is depicted by the solid blue line. The solid orange line depicts an infalling observer.

However, according to Postulate 4, there should be absence of drama for an infalling observer. Hence the observer should measure the ground state with no deviations from the classical Unruh vacuum. Suppose an infalling observer is counting the high-energy modes with a measuring apparatus. Following Postulate 4, the expectation value should be zero, $N_i = 0$, where $N_i = a_i^\dagger a_i$. As AMPS have pointed out, this statement appears to be in contradiction with our nomenclature regarding quantum field theory in curved spacetime (Postulate 2). As Hawking has explicitly shown in his semiclassical calculations [3] the strong gravitational field acts on the quantum vacuum and polarizes the virtual particle pairs. The number of the produced particles which are radiated away to infinity is thus given by

(2) $$<0|a^\dagger_i a_i|0>=\Sigma_i|\beta_i|^2$$

By finding the value of β we approximate the number of the emitted quanta. As it follows from black hole perturbation theory [4, 5] as the hole evaporates it loses mass which leads to an increase of the temperature, and thus faster evaporation rate. Although the value of β is small, the effects of the black hole's mass on the matter fields add up during the course of evaporation, and should be significant after Page time. Therefore, after half of the black hole has evaporated the number of out-modes, that an infalling observer carrying measuring apparatus will count, should be non-zero, hence causing drama and contradicting Postulate 4.

Because of the contradiction between the postulates of complementarity, AMPS argue the following three statements cannot all be true:

(i) Purity of the emitted Hawking quanta.

(ii) Absence of drama for an infalling observer.

(iii) Semiclassical physics in the vicinity of the black hole.

Oscillations as stretched horizon

We address the question of what boundary conditions need to be present at the vicinity of the event horizon in order to avoid formation of a firewall for a sufficiently old black hole. As it has been argued in Sec. I, AMPS' argument leads to violation of the no-drama principle after Page time if there is an entanglement, i.e.maximal correlation, between early- and late-time Hawking radiation. It has been shown in [6] that disentangling the quantum vacuum in the near-horizon region by introducing certain boundary conditions preserves the effective field theory for old black holes. The imposed boundary conditions have to meet certain requirements, namely to change the correlation between the in- and out-modes without affecting the thermal spectrum of the radiation emitted to I^+, and preserve the conservation of momentum. Even small deviations from the purely thermal spectrum of the Hawking particles will lead to stress-energy divergence due to the large blueshift which occurs when an observer at I^+ traces the particles to the origin. In that case, $T_{\mu\nu} \to \infty$ as $r \to 2M$.

As it has been suggested in [2, 6] as far as a far away observer is concerned there is a stretched horizon (physical membrane) located l_P away from the global horizon ($r = 2M$) in outward direction. The proposed membrane acts as a partially reflecting mirror with the following characteristic

(3) $$\Phi_{out} - \Phi_{in} = 0$$

where *in* and *out* stand for coming from I^- and radiated to I^+, respectively. Thus an observer at I^+ can obtain all of the information from I^- and vice versa. The reflective property implies we preserve the unitary evolution of the S-matrix and establish time-symmetric map between past and future null infinity. As a result the stress-energy tensor is normalized. That being said, the conditions imposed in [6] lead to polarization of the particle pairs solely on one side of the horizon, either $r < 2M$ or $r > 2M$, and hence break the trans-horizon correlations.

We argue the Planckian-amplitude horizon oscillations [7] can generically account for the suggested boundary conditions. The conjectured oscillations arise naturally from perturbation theory. The effect is argued to be caused by transformation of coarse-grained degrees of freedom into fine-grained degrees of freedom which is an integral part of the black hole formation/evaporation process. Furthermore, the frequency of the oscillations solely depends on the mass of the hole

(4) $$\omega = \sqrt{\frac{-T_{\mu\nu}}{M}}$$

where $T_{\mu\nu}$ is the emitted Hawking radiation and M is the mass of the black hole. We suppose the horizon oscillations can account for both, vacuum disentanglement and the partially reflecting boundary surface.

Let's suppose we have a spherically symmetric collapse given by the Schwarzschild metric

(5) $$ds^2 = -(1-(2M/r)dt^2 + (1-2M/r)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\varphi^2)$$

In the context of complementarity an observer at I^+ would measure the entropy of the black hole to emerge from the fine-grained degrees of freedom outside the global horizon (stretched horizon). As it has been argued in [2] each point from the global horizon ($r = 2M$) is projected onto a physical membrane located a l_P away. Hence the whole surface is shifted by order of δ, where δ is a small positive constant. Therefore the entropy of the event horizon equals the entropy of the stretched horizon which obey the Bekenstein bound in Planck units, $S_{horizon} = S_{stretched} = A/4$. Because of the established equality we argue the oscillations can account for the physical membrane as far as an observer at I^+ is concerned.

Since the black hole polarizes the quantum vacuum in the vicinity of its horizon, we argue the proposed oscillations are sufficient to produce the desired effect, namely the particle pairs remain in either the interior or exterior region thus breaking up the vacuum entanglement. Suppose we have a collapse in initially pure state

(6) $$|\psi\rangle = \Sigma_i |\psi\rangle \otimes |i\rangle$$

where $|\psi\rangle \in \mathcal{H}_{out}$ and $|i\rangle \in \mathcal{H}_{in}$. Here $\mathcal{H}_{out}$ and $\mathcal{H}_{in}$ stand for radiation emitted to infinity and radiation close to the horizon, respectively. For a black hole after Page time we assume $|\psi\rangle > |i\rangle$. If we interpret the radiated Hawking particles in terms of Hilbert spaces, we get $dim(\mathcal{H}_{out}) \gtrsim dim(\mathcal{H}_{in})$ [8]. That being said, when an observer at I^+ traces the Hawking quanta back to the origin no deviations will be observed due to the purely thermal spectrum of the emission. Moreover, when the out-modes are traced back no membrane will be present. As far as a close-by observer is concerned infalling matter is not reflected by a stretched horizon, and crosses the $r = 2M$ region with no drama. We argue there will be discrepancy between the reference-based description of order t_S, where $t_S = R\, ln(R/l_P)$, due to the lack of perturbation to the background metric caused by infalling matter. A close-by observer should see matter being radiated away from the global horizon, hence being reflected by the singularity region (dS core) [7] of order t_S later.

So far we have provided a complementary description of the physical membrane, and have shown how the conjectured horizon oscillations can account for it. However, we still have not addressed the question of what causes the infalling matter reflection, as reported by an observer at I^+.

Spherically symmetric solutions to Einstein field equations describe generic collapse with the horizon region being a flat plane with no special dynamics. Quantum vacuum in asymptotically flat spacetime with a boundary surface leads to ambiguity (Casimir effect). Thus the number of measured eigenstates $a_i^\dagger a_i$, will be observer dependent. Let's suppose we have a pair of observers, Alice and Bob, each carrying a measuring apparatus, where Alice is close to the event horizon, and Bob is far away. We expect Alice and Bob to disagree on the number of the produced eigenstates in the near-horizon region

(7) $\varphi = \sum_i (a_i^\dagger f_i^* + a_i f_i)$

(8) $\varphi = \sum_i (b_i^\dagger f_i^* + b_i f_i)$

hence they measure different number of particles, $N_A \neq N_B$. It has been suggested in [9, 10] that tracing back the outgoing modes from I^+ to the horizon will result in various vacua, all locally indistinguishable (vacuum degeneracy). The observer close to the horizon,i.e. Alice, will not encounter high-energy particles but rather Unruh vacuum (Postulate 2). The number of different vacua, $|\psi_n>$ surrounding the horizon is given by the exponential of the Bekenstein-Hawking area/entropy bound in Planck units, $exp[A/4]$. The number $|\psi_n>$, equals the entropy of the global horzion $S_{horizon}$, and therefore the entropy of the stretched horizon $S_{stretched}$. The effective uniqueness of the quantum vacuum allows for information to be stored onto it without getting energetically excited (Postulate 4). That being said, we argue that a distant observer, i.e. Bob, can falsely interpret the information stored onto the degenerate vacuum as a partially reflective surface. As far as Bob is concerned, infalling matter gets thermalized, and reflected back by the stretched horizon. Moreover, the out-modes emitted to infinity are also seen to originate from the physical membrane, from the perspective of an observer at I^+. For Alice, however, who is at proper distance r from the black hole nothing unusual happens. Infalling matter experiences no drama, and the Hawking particles are emitted from the global horizon ($r = 2M$).

Conclusion

We have shown that the generic phenomena of Planckian-amplitude horizon oscillations can account for the stretched horizon proposed in black hole complementarity, and also provide the necessary conditions for breaking up the entanglement between early- and late-time Hawking particles; thus preventing the formation of a firewall after Page time. The conjectured oscillations follow from classical black hole perturbation theory. The model builds on the complementary picture given by Susskind by providing natural explanation of its basic features.

References

1. Almheiri, A., D. Marolf, J. Polchinski, and J. Sully, Black Holes: Complementarity or Firewalls?, J. High Energ. Phys., 10.1007/JHEP02(2013)062.
2. Susskind, L., L. Thorlacius, J. Uglum. The stretched horizon and black hole complementarity. Physical Review D: Particles and Fields. 48, 3743–3761. PMID: 10016649, DOI: 10.1103/PhysRevD.48.3743.
3. Hawking, S. W., Particle creation by black holes, Phys. 43, 199220 (1975).
4. Paolo Pani, Advanced Methods in Black-Hole Perturbation Theory, arXiv:1305.6759v2 [gr-qc].
5. Mino, Y., M. Sasaki, M. Shibata, H. Tagoshi, and T. Tanaka, Black Hole Perturbation, Prog. Theor. Phys. Suppl. 1997, 128, 1–121.
6. Hossenfelder, S., Disentangling the Black Hole Vacuum, Phys. Rev. D. 2015, 91(4) 044015. DOI: 10.1103/PhysRevD.91.044015
7. Yosifov, A., and L. Filipov, Black Hole Horizon Oscillations, Aerospace Research in Bulgaria, 2016, 28, 19–31.
8. Nomura, Y., J. Varela, and S.J. Weinberg, Complementarity Endures: No Firewall for an Infalling Observer, arXiv:1207.6626v4 [hep-th].
9. Hawking, S.W., M.J. Perry, and A. Strominger, Soft Hair on Black Holes, Phys. Rev. Lett. 2016, 116(23), 231301. DOI: 10.1103/PhysRevLett.116.231301
10. Hossenfelder, S. Comment on the black hole firewall, arXiv:1210.5317v1 [gr-qc].

ТРЕПТЕНИЯ НА ХОРИЗОНТА ЗА ЗАПАЗВАНЕ НА ПРИНЦИПА НА ЕКВИВАЛЕНТНОСТТА

А. Йосифов, Л. Филипов

Резюме

Представяме принцип, който описва група от гранични условия за запазване на ефективната теория на полетата след време на Пейдж. Също така предлагаме сценарий, който описва физическата мембрана от комплементарността при черни дупки, без да е наличен разгънат хоризонт от гледна точка на отдалечен наблюдател.