Thought Experiment to resolve the Black Hole Information Paradox

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Abstract

We propose a combination of two mechanisms that can resolve the black hole information paradox. The first process is that the black hole shrinks by a first order transition, since we assume the entropy is discontinuous. The black hole disappears. The second type of processes conserves unitarity. We assume that within the black hole micro-reversible quantum mechanical processes take place. These are ordinary particle processes, e.g. the decay of an electron and a positron into two photons.

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I. INTRODUCTION

In 1975 Hawking [1] proposed, that black holes are quantum mechanically not black. This means that particles are created within black holes. They emit particles and evaporate. The effect is called Hawking radiation. Hawking computed the probability of particle creation of a gravitational field within a black hole. Frolov and Novikov [2] have been summarized the basics of particle creation: Let $\Gamma$ be the field strength and $g$ the charge of the particle being created. To find the particles of a virtual pair at the distance $l$ from one to another the probability $w$ is proportional to $\exp(-l/\lambda_m)$, where $\lambda_m = \hbar/mc$ is the Compton length for a particle of mass $m$. The probability is exponentially small for distances larger than the Compton length $\lambda_m$. For a real particle the same factor of the exponential function enters the probability. In the probability amplitude of a static field a $\delta$-function appears. It follows that energy is conserved. The amplitude only vanishes, if the work $g\Gamma l$ by the field over the distance equals $2mc^2$. It follows for the Hawking pair production that the probability $w$ is proportional to $\exp(-2mc^3/h\sigma\Gamma)$. The pair production process should require tunneling of a particle. The factor in the exponent of the probability is nothing more than the Euclidean action of the tunnel effect. The full probability is expressed as:

$$w = A \exp(-\beta \pi m^2 c^3/h\sigma \Gamma).$$  \hspace{1cm} (1)

$A$ is the amplitude. It is dimensionless and depends on the nature of the field. $\beta$ is also dimensionless, in the order of unity, and also depends on characteristics of the field. The tunnel effect leads to a factor $\pi/2$ for a particle of electric charge. In the theory of gravitation the charge is represented by the mass $m$, so:

$$w = A \exp(-2mc^2/\theta), \text{ with } \theta = \frac{h\Gamma}{\beta \pi c}.$$  \hspace{1cm} (2)

Hawking [1, 3] evaluated that a vacuum is unstable in the presence of a black hole. The emission spectrum is that of a black body with a temperature $T_H$ of:

$$T_H = \frac{h\kappa}{2\pi ck_B},$$  \hspace{1cm} (3)

where $k_B$ is the Boltzmann constant, and $\kappa$ is the surface gravity that characterizes the "strength" of the gravitational field in the vicinity of the black hole surface. For a Schwarzschild black hole

$$\kappa = \frac{c^4}{4GM},$$  \hspace{1cm} (4)
and the Hawking temperature becomes:

\[ T_H = \frac{\hbar c^3}{8\pi GMk_B}. \tag{5} \]

If one neglects the scattering effects of the created particles by the gravitational field, at infinity the probability, that a particle with energy \( E \) is created, becomes

\[ w \propto \exp(-E/k_B T_H). \tag{6} \]

Hawking radiation yields to the reduction of the black hole area. Based on energy conservation, this implies that there must be a flux of negative energy through the horizon into the black hole. Hawking concluded the black hole evaporates. All information is lost and unitarity is violated \[4\].

Based on the work of 't Hooft \[5, 6\], and Preskill \[7\] Susskind et al. \[8\] invented an idea to save unitarity that is called complementarity. They start off from:

**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 \( S \)-matrix which describes the evolution from infalling matter to outgoing Hawking radiation.

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

**Postulate 3** To a distant observer, a black hole can be described by discrete energy levels. The dimension of the subspace of states describing a massive black hole of mass \( M \) is the exponential of the Bekenstein entropy \( S(M) \) \[9\].

**Postulate 4** A free falling observer experiences nothing out of the ordinary when crossing the horizon \[10\].

A black hole consists to the outside observer of something, which is called "stretched horizon" or physical membrane. The properties of the membrane are time-irreversible and dissipative. An outside observer will notice that. On the other hand other observers will not agree to this. Experiments will show that the effects of the physical membrane appear or appear not depending on the position of the observer. This phenomenon is called black
hole complementarity. It does not solve the problem of unitarity.

Almheiri et. al. [10, 11] recently proposed a new paradox (cf. Braunstein [12] published as Braunstein et. al. [13], for a similar prediction from different assumptions). Almheiri et. al. starts off from the postulations by Susskind et. al. [8]. They considered a very big black hole. A freely falling observer passing the event horizon sees an effectively flat spacetime, since the scale is much smaller compared to the whole event horizon. Hawking radiation has been divided into an early and a late time part. Postulate 1 implies that through the division the fate of the black hole could be described entirely by standard quantum mechanics. It follows [14]: For an observer who observes from the outside of the horizon, the possibility of describing the system by standard quantum mechanics yields to the fact that late time radiation must be maximally entangled with early time modes. Now let the late time radiation reach the near horizon from infinity. From the point of view of a freely falling observer the late time radiation must be maximally entangled with modes from inside the black hole. The strong subadditivity of entangled entropy does not allow this. The maximal entanglement with modes from the inside of the black hole can only be avoided, if the photon is entangled with radiation that is not behind the horizon. This would lead to a stress tensor that is divergent near the horizon, and the freely falling observer would burn up before crossing it. This so-called ”firewall” has been discussed [15–27]. All assumed that the central singularity remain.

Hawking [28] found objections to the firewall approach by Almheiri et. al. [10, 11]. The results of his ideas are: If one assumes quantum gravity is CPT invariant it rules out remnants, event horizons, and firewalls. The absence of event horizons means black holes are no black holes anymore. The metric and the matter fields inside the object will be classical chaotic. Information is effectively lost but unitarity is conserved. A black hole will radiate deterministically but chaotically. The situation is like a weather forecast on earth, which is only possible for a couple of days.

Vaz [14] computed a Wheeler-DeWitt equation for a black hole as a gravitational atom. He found an apparent horizon. In order to avoid a firewall a ”dark star” forms and a central singularity does not arise.

Mersini-Houghton [29] predicted the absence of a central singularity and a horizon of a black hole: She calculated the backreaction of negative energy Hawking radiation of the interior of a symmetric collapsing star. The interior of a star is assumed in that calculation as a
closed Friedmann-Robertson-Walker Universe for as long as she matches the Friedmann-
Robertson-Walker metric at the surface of a star to the Schwarzschild metric \[30, 31\].

Shortly afterwards Vaz \[32\] computed a Wheeler-DeWitt equation of a collapsed dust star.
He evaluated an exact quantization of dust collapse. As Vaz pointed out: It provides an
evaluation of the radius in which quantum fluctuations dominate. Quantum fluctuations pro-
duce a negative mass point source at the center. The mass decreases negatively towards the
Schwarzschild radius where it disappears. The fluctuations occupy the entire Schwarzschild
radius of the star. He predicted that in his model exists no region of a horizon. He provided
a condition for which no singularity can form. Vaz predicted a redshift of radiation compa-
rable to that of a neutron star.

All three computations do not resolve the black hole information paradox. The calcula-
tions above have been assumed that Hawking radiation is present. Hawking radiation is not
micro-reversible, since particles are only created and one particle leaves the black hole while
the other is absorbed by the negative interior of the black hole.

We present our thought experiment, where the black hole evaporates itself by ordinary
micro-reversible processes in Sec. II. The gravitational field is smooth, deterministically,
chaotically, and continuously converted by a first order transition to Minkowski spacetime
(that the transition from the gravitational field to Minkowski spacetime can be regarded
as a phase transition, has been discussed in a spontaneous symmetry breaking theory by
Requardt \[33\]). Sec. III finishes the paper with results and a discussion.

II. THE THOUGHT EXPERIMENT

Ordinary pair production, e.g.:

$$e^+ + e^- \rightarrow 2\gamma,$$

(7)

is reversible, like any microscopic particle process. Our phase transition does not start with
the creation of particles by the gravitational field. It starts, e.g. with an electron, and a
positron destroyed by the gravitational field, and two photons created.

The fate of a black hole ensues mainly three possible outcomes after the semi-classical
approximation is not applicable anymore. It is not applicable anymore, when the black hole
has been shrunk to the Planck radius. The outcomes are \[2\]:
1. The black hole can completely disappear, and the information can completely disappear from our world.

2. The black hole can disappear but the information is released back.

3. There remains a stable remnant.

We propose that effectively 1. is correct. In conventional theories the last step of the evaporation process is reached when one arrives at the Planck mass, and it appears a singularity (for an essay about the history of the development of the term singularity, and the different ideas of singularities see [34]), where the semi-classical picture breaks down, and the curvature tends to infinity [35–38]. Moreover unitarity is violated. These are unsatisfying points in the conventional theories of black holes, since the laws of physics break down.

We argue that the so-called remnants on Planck scales \( m_{\text{pl}}, l_{\text{pl}} = \sqrt{\hbar G/c^3} \simeq 1.1616 \times 10^{-35}m \) are not only made of curvature. This implies not only the idea of a Planck mass \( m_{\text{pl}} = \sqrt{\hbar c/8\pi G} \simeq 4.31 \times 10^{-9}kg \). Moreover remnants, if they exist, are also made of matter and anti-matter, since Einstein’s equations of motion require additionally to the Einstein tensor the energy-stress tensor, which is the source of the gravitational field. Since we assume that the gravitational field is able to destroy particles, we can conclude ordinary decay processes are able to finish the evaporation process leaving a vacuum, while releasing radiation. We conclude that remnants do not occur.

In our thought experiment we will assume that ordinary particle processes are part of the process that resolves the information paradox. Regarding thermodynamics the start point of our thought experiment of evaporation of the black hole is the isolated black hole built up by the collapse of a star. The end of the process is totally released radiation and effective loss of information.

Thermodynamics of black holes are related to ordinary thermodynamics. The first law of black hole thermodynamics is given by [39]

\[
dM = \frac{\kappa}{8\pi}dA + \Omega dJ, \tag{8}
\]

where \( A, M, \Omega, J \) are entropy, mass, angular velocity, and angular momentum. Total entropy of the system is black hole entropy \( S_{BH} \), i.e. the area \( A \) of the black hole plus von Neumann entropy \( S_{VN} = -tr(\rho \ln \rho) \) (\( \rho \) being a density matrix):

\[
S = S_{BH} + S_{VN}. \tag{9}
\]
We assume that the process of evaporation is a first order transition that constitutes a two-phase system. This is due to a discontinuous entropy. It results in a latent heat of the system. If no horizon is formed or only an apparent horizon arises the curved area is converted deterministically, chaotically and continuously to Minkowski spacetime, which is one part of the first-order transition system. The other part is released radiation. As already pointed out we propose that together with the radiation a black hole constitutes a two-phase system. Quantum gravity becomes relevant at Planck scales. The gravitational field of a black hole is so strong that particles can be created, and we propose can also be destroyed. In case of Hawking radiation an observer from the outside of a black hole can only observe a part of the quantum system. In Hawking’s theory, only one of two particles being created can leave a black hole since the states with negative energy are in a black hole. Here lies the difference between our proposal of ordinary quantum particle decay processes as the responsible effect that leads to the evaporation of a black hole, and Hawking radiation. We propose that Minkowski spacetime contains the states of negative energy. The gravitational field acts regarding Minkowski spacetime, e.g. as a field which is inducing a pair production. Thus e.g. photons being destroyed and an electron and a positron are created and are able to leave a black hole. The microscopic process is reversible. Incoming information converted by the same procedure described above, means the gravitational field acts as the source for conversion.

III. RESULTS AND DISCUSSION

Hawking [28] considered a black hole as an entity, which is not a black hole anymore, since it contains no event horizon. The object will radiate deterministically, but chaotically like a weather forecast on earth. That means it cannot be predicted for a long time. In the end all information is effectively lost. Computing a black hole as a gravitational atom Vaz [14] found out that avoiding a firewall the system contains no singularity. Mersini-Houghton [29] supported the view by Hawking that no event horizon is built up. She predicted that, regarding the backreaction of Hawking radiation onto a star’s collapse curvature, in a black hole no horizon and no singularity at all form. Later Vaz [32] supported the idea by Hawking that no event horizon and under specific circumstances no singularity can form. These ideas do not conserve micro-reversibility.
We present a thought experiment that can resolve the black hole information paradox. Our thought experiment can explain the effects that Hawking was not able to explain. It is based on two ideas. Firstly particles are destroyed, and are created like in, e.g. ordinary decay processes. This is due to the strong gravitational field, that regarding Minkowski spacetime acts like, e.g. a field that induces a pair production of an electron and a positron. Secondly the curved area is smooth, deterministically, chaotic, and continuously converted by a first order transition to Minkowski spacetime.

After formation of a black hole its evaporation begins. What was previously a black hole shrinks and disappears. The system black hole and its radiation constitute a first order transition process. In our case it consists of a discontinuous entropy. The discontinuous entropy results in a latent heat. Temperature remains constant in the two-phase system, i.e. in the area of the black hole plus its radiation during the process of shrinkage. A von Neumann entropy is built up, but micro-reversibility is conserved. Total entropy $S = S_{BH} + S_{VN}$ increases always.

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