Reflection on event horizon and escape of particles from confinement inside black holes

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Several recently found properties of the event horizon of black holes are discussed. One of them is the reflection of the incoming particles on the horizon. A particle approaching the black hole can bounce on the horizon back, into the outside world, which drastically reduces the absorption cross section in the infrared region. Another, though related phenomenon takes place for particles inside the horizon. A locked inside particle has, in fact, an opportunity to escape into the outside world. Thus, the confinement inside the horizon is not absolute. The escape from within the interior region of the horizon allows the transfer of information from this region into the outside world. This result may help resolve the information paradox for black holes. Both the reflection and escape phenomena happen due to pure quantum reasons, being impossible in the classical approximation.

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I. INTRODUCTION

A progress related to several quantum phenomena that take place on the event horizon of black holes is outlined. One of the effects discussed here is the well known Hawking radiation. The other two phenomena examined were found only recently. They are the reflection on the event horizon of black holes, and the escape of particles from the confinement within the inside region of the horizon into the outside world.

The effect of the Hawking radiation [1, 2], and the closely related Unruh process [3], have links with the entropy of black holes studied by Bekenstein [4, 5, 6]. For a recent review on the Hawking effect and thermodynamics properties of black holes see [7, 8]. Treatment of quantum phenomena on the event horizon, including the problem of the origin of the entropy of black holes, the density of its quantum states, and the brick wall model can be found in the reviews by ’t Hooft [9, 10], see also his Ref. [11].

The phenomenon of reflection on the event horizon, which will be discussed in detail in this work, has strong connections with the scattering problem. The first analytical results in the scattering problem were obtained by Starobinsky [12] for the scalar field and Starobinsky and Churilov [13] for electromagnetic and gravitational waves scattered by the rotating Kerr black hole. Independently, Unruh [14] considered scattering of scalar and fermion particles by Schwarzschild black holes. A detailed study of the scattering problem was given by Sanchez [15, 16]. After these and a number of subsequent works, it has been assumed that the scattering problem is completely understood, see details and bibliography in the books [17, 18, 19, 20].

However, it was found recently in Refs. [21, 22, 23] that a particle approaching the black hole can bounce on the horizon back into the outside world. This phenomenon is referred to below as the reflection on the horizon (RH). The effect arises due to pure quantum reasons, being obviously absent in the classical approximation. The RH prompts a strong decrease in the absorption cross section, reducing it to a zero value in the infrared region, as was shown explicitly in [24] for scattering of scalar massless particles on Schwarzschild black holes. This behavior of the cross section differs qualitatively from the previously accepted result, which stated that the low energy absorption cross section equals the area of the horizon [14]. The similar reduction of the cross section is expected to take place for scattering of any massless particle by any black hole in the low energy limit.

The quantum phenomena that prompt the existence of the RH have another unexpected manifestation, for particles confined inside the horizon. Classically this confinement is absolute. However, the quantum treatment of the problem in Refs. [21, 22, 23] revealed that the wave function of any confined particle necessarily has a particular admixture that behaves on the horizon as the outgoing wave. This property of the wave function indicates that any confined particle has a chance to escape from the inside region into the outside world. Thus, the confinement inside a black hole is not perfect, a particle locked inside has a chance to find its way out. We will refer to this opportunity as the escape effect (EE). The Hawking radiation process can be considered as a manifestation of the EE in particular circumstances, when a black hole is put inside the temperature bath. However, in the general case the EE allows the extraction of information from the inside region of the horizon into the outside world.

This work briefly summarizes some of the arguments of [21, 22, 23, 24] related to the RH and EE. Units $\hbar = c = 2G = M = 1$ are used, where $G$ and $M$ are the gravitational constant and the black hole mass; the gravitational radius in these units reads $r_g = 2G/c^2 = 1$. 
II. REFLECTION ON HORIZON

Let us formulate briefly the results of Refs. [21, 22, 23]. Consider for simplicity the scalar massless field in the vicinity of the Schwarzschild black hole. Take a scalar particle with the energy $\varepsilon$ and zero orbital momentum $l = 0$. It is easy to verify (see e. g. (17, 18, 19, 20), or Eqs. (4.5), (4.6) below) that the corresponding wave function exhibits behavior $\phi(r) \simeq \exp[-i\varepsilon \ln(r - 1)]$ on the horizon $r \to 1$, where the signs minus and plus describe the waves propagating inside and outside of the horizon respectively. The general form of the wave function on the horizon is therefore

$$\phi(r) \simeq \exp[-i\varepsilon \ln(r - 1)] + R \exp[i\varepsilon \ln(r - 1)] , \quad (2.1)$$

Suppose we consider the scattering problem, the impact of scalar particles on the black hole. Then the first term in Eq. (2.1) is definitely present, it describes the flux of incoming particles. It seems also natural to expect that there is no second term, because the horizon is presumed to be a perfect absorber. In other words, it seems natural to put in Eq. (2.1) $R = 0$. Exactly this condition has always been used in the scattering problem for different particles (scalars, spinors, electromagnetic and gravitational waves) and different types of black holes (Schwarzschild, Kerr and others), see the pioneering Refs. [12, 13, 14], later developments can be found in the review [15] and books [17, 18, 20].

It was unexpected therefore that Refs. [21, 22, 23] argued that $R$ in Eq. (2.1) has, in fact, a nonzero value, specifically that

$$|R| = \exp\left(-\frac{\varepsilon}{2T}\right) , \quad (2.2)$$

where $T = 1/(4\pi)$ is the Hawking temperature. The fact that $|R| > 0$ means that there is a reflected wave in Eq. (2.1) that gives rise to the flux of outgoing particles. Correspondingly, $R$ is to be called the reflection coefficient. The fact that it is nonzero indicates that a particle can bounce on the horizon back into the outside world. Eq. (2.2) presents an explicit form for the effect that was called the RH in Section III. For low energies $\varepsilon < T$ the RH is very effective, which makes the horizon a good reflector in the infrared region. This property is in contrast with the conventional point of view that presumes the horizon to be a perfect absorber.

Eq. (2.2) has a profound influence on the absorption cross section for low energies of incoming particles $\varepsilon \leq T$. Assuming conventional properties of the horizon ($R = 0$) Unruh found [14] that in the infrared region the cross section equals the area of the horizon

$$\sigma_{\text{abs}} = 4\pi r_g^2 , \quad \varepsilon \to 0 . \quad (2.3)$$

(Here and in Eq. (2.4) below conventional units are used.) Taking the RH into account Ref. [23] arrived at a different result

$$\sigma_{\text{abs}} = 4\pi^2 r_g^3/(\hbar c) , \quad \varepsilon \to 0 , \quad (2.4)$$

which means that the cross section vanishes for low energy.

There is an appealing physical picture suggested in [24] that describes the RH as a creation of a pair at the horizon followed by an annihilation of one of the created particles with the inner particle inside the black hole. This is close to the usual physical explanation of the Hawking effect via the pair production [31].

Eqs. (2.1), (2.2), and (2.3) summarize the main claims that Refs. [21, 22, 23] made for the outside region. Later on, in Section IV, we will discuss the implications of these results for the inside region.

III. LARGE WAVELENGTHS

The book of Khriplovich [25] mentions qualitative arguments put forward by Gribov in early 70’s, which indicated that black holes are capable of radiating. One of his reasons, as the book presents it, was that “it is obvious that a black hole is incapable of containing radiation with the wavelength exceeding the gravitational radius” (p. 112 of [25] in our translation from Russian). This argument may look simplistic (though it was not the only one articulated by Gribov), but keeping in mind that it was made before the Hawking finding, its simplicity bears, arguably, an aura of a classical foreseeing.

If one allows oneself to rely on this argument in the scattering problem, one has to conclude that the absorption of particles with large wavelengths by a black hole should meet a difficulty, in other words it should be suppressed. This is exactly what Eq. (2.3) which takes the RH into account predicts. In contrast, Eq. (2.4) which neglects the RH shows no sign of such suppression. Thus, one may argue that the RH is in line with the Gribov argument related to large wavelengths.

IV. REFLECTION ON HORIZON AS ABOVE-BARRIER REFLECTION

Let us discuss a simple argument used in Refs. [22, 24] to justify validity of the RH. Consider the Schwarzschild geometry with the metric

$$ds^2 = -\left(1 - \frac{1}{r}\right)dt^2 + \frac{dr^2}{1 - 1/r} + r^2d\Omega^2 , \quad (4.1)$$

where $d\Omega^2$ describes the contribution of angular variables. Take the scalar field, assuming for simplicity that it is massless. Choose the most important for us wave with the zero orbital momentum $l = 0$. Then the radial wave function $\phi(r)$ for the stationary state with energy $\varepsilon$ satisfies the Klein-Gordon equation

$$\phi''(r) + \left(\frac{1}{r} + \frac{1}{r - 1}\right)\phi'(r) + \frac{\varepsilon^2}{(1 - 1/r)^2}\phi(r) = 0 . \quad (4.2)$$
Making the substitution $\phi(r) \rightarrow \psi(r) = [r(r-1)]^{1/2} \phi(r)$ one can rewrite Eq. (4.2)

$$\varepsilon^2 \psi(r) = -\psi''(r) + U(r) \psi(r) ,$$

where

$$U(r) = -\frac{1}{(r-1)^2} \left( \frac{\varepsilon^2}{4r^2} - \frac{2\varepsilon^2}{r-1} \right).$$

reducing it to the form of the conventional Schrödinger-type equation, if $U(r)$ is considered as an effective, energy-dependent potential (note that it is strictly attractive), and $\varepsilon^2$ on the left-hand side is accepted as the eigenvalue. 

Consider the scattering problem, the impact of scalar particles on the black hole. Then, definitely there is the incoming wave that falls on the horizon. In the proximity of the horizon $|r-1| \ll 1$ this wave reads

$$\phi_{in}(r) = \exp[-i\varepsilon \ln(r-1)], \quad r > 1,$$

as can be verified using Eq. (4.2), or (4.3).

Let us look at the problem from the traditional point of view. There is the incoming wave Eq. (4.5), and there is the potential Eq. (4.4). One can expect therefore that there should exist also the outgoing wave, which is always present in quantum mechanical problems of this type. This is true even for attractive potentials. The only distinction for the attractive potentials is that the reflection for them is prompted by pure quantum reasons, being absent in the classical approximation. As a result, the reflection coefficient is to be exponentially small. In the problem at hand, the potential $U(r)$ in Eq. (4.4) is smooth in the region $r > 1$, the semiclassical approximation works well for it, with the only exception of the horizon $r = 1$, where the potential has a singular point $U(r) \sim -(\varepsilon^2 + 1/4)/(r-1)^2$.

We can apply therefore conventional semiclassical methods by taking the incoming wave Eq. (4.5) and continuing it into the region $r < 1$ by means of the analytical continuation over the lower semiplane of the complex plane $r$ that avoids the singularity at $r = 1$. The result, which reads

$$\phi_{in}(r) = \exp[-\pi \varepsilon - i\varepsilon \ln(1-r)], \quad r < 1,$$

shows that the incoming wave exists in the inside region $r < 1$. We need to determine therefore what happens to the wave function at the origin $r = 0$, where, generally speaking, it behaves as $a + b \ln r$. As usual, a solution regular at the origin should be chosen. Such a solution cannot be constructed from the incoming wave Eq. (4.6), which necessarily incorporates the part singular at $r = 0$. We derive from this fact that in the region $r < 1$ there should exist also the outgoing wave, which combines with the incoming wave to make the total wave function regular at the origin. In the vicinity of the horizon the outgoing wave can be presented as

$$\phi_{out}(r) = \exp\left[-\pi \varepsilon + i\varepsilon \ln(1-r) + i\alpha \right], \quad r < 1.$$ 

It has the same magnitude as the incoming wave (to allow a compensation of their singular parts at the origin), shifted, possibly, by a phase $\alpha$ that depends on details of the wave propagation far away from the horizon.

This outgoing wave can now be continued into the region $r > 1$ by using (again) the analytical continuation over the lower semiplane of the complex plane $r$. As a result we find that there exists the outgoing wave in the outside region

$$\phi_{out}(r) = R \exp[i \varepsilon \ln(r-1)], \quad r > 1,$$

where the coefficient is

$$R = \exp(-2\pi \varepsilon + i\alpha).$$

We come to the important conclusion. Alongside the incoming wave Eq. (4.5), the wave function necessarily incorporates also the outgoing wave Eq. (4.8), in agreement with Eq. (2.4). The value for the reflection coefficient Eq. (4.9) found here supports Eq. (2.2). This reflection coefficient is exponentially small for high energies, in accord with the naive anticipation for scattering on an attractive potential.

In conclusion, the effective attractive potential Eq. (4.4), which is associated with the horizon, is able to reflect the incoming wave, which means that the RH really takes place. The effect has a similarity with the well known quantum phenomenon of the above-barrier reflection. The methods used here for its derivation are close to the conventional semiclassical treatment of the above-barrier reflection.

V. DISCRETE SYMMETRY OF SCHWARSCHILD GEOMETRY

Let us discuss another argument in favor of the RH, which was presented in [21,22]. Consider the wave function $\phi(r)$ as an analytical function defined on the complex plane $r$. Take the real, physical value for $r$ in the vicinity of the horizon, $r > 1$, $r-1 \ll 1$, where Eq. (2.4) is valid; then rotate $r$ around the point $r = 1$ on the complex plane $r$ over an angle of $2\pi$ clockwise. Since we can keep $|r-1| \ll 1$, we can rely on Eq. (2.4) throughout this transformation. The transformation results in a new wave function $\tilde{\phi}(r)$

$$\tilde{\phi}(r) = \varrho \exp[-i\varepsilon \ln(r-1)] + \frac{R}{\varrho} \exp[i\varepsilon \ln(r-1)], (5.1)$$

where

$$\varrho = \exp(-2\pi \varepsilon).$$

The important feature of the problem is the discrete symmetry of the Schwarzschild geometry. It can be expressed as a condition on functions $\phi(r)$ and $\tilde{\phi}(r)$

$$[\tilde{\phi}(r)]^* = \exp(-i\alpha)\phi(r),$$

\begin{align*}
\frac{1}{m} \frac{d}{dr} \left( r^2 \frac{d}{dr} \phi \right) &= -m^2 \phi,
\end{align*}
where $\alpha$ is a phase, which is not determined by this condition. The origin and physical meaning of this symmetry are discussed below, see Eqs. (5.6). Meanwhile, to conclude the argument, note that from Eqs. (5.3), (5.4) one immediately finds that the reflection coefficient $R$ satisfies Eqs. (4.1) and (2.2), thus verifying the RH.

It is convenient to look at the presented argument using Kruskal [26] coordinates $U,V$

$$U = - (r - 1)^{1/2} \exp \left( \frac{r - t}{2} \right),$$
$$V = (r - 1)^{1/2} \exp \left( \frac{r + t}{2} \right).$$

They are shown in Fig. 1 in the conventional form, see e.g. Ref. 27. One observes that the rotation over the angle $2\pi$ around the point $r = 1$ on the complex plane $r$ described above leads to the transformation $U \rightarrow U'' = -U$, $V \rightarrow V'' = -V$, which brings the point $A$ on the Kruskal plane in Fig. 1 to the point $A''$ in the region III via the complex intermediate values of the variables $U, V$. The regions I ($U < 0, V > 0$) and III ($U > 0, V < 0$) of the Kruskal plane describe events that take place in the outside world [27]. These two regions are known to be identical, which provides an opportunity to describe each event in the outside world by one of the two points, either by the one located in the region I, or by the other one located in the region III.

If some event is described by a point $A$ that has the coordinates $U, V$ in the region I, then the point $A'$, which represents the same event in the region III, has the coordinates $U', V'$, where $U' = V, V' = U$, see Fig. 1. This identification of the points $A$ and $A'$ is particularly transparent in the vicinity of the event horizon that surrounds the internal region II in which all classical trajectories lead towards the singularity at $r = 0$. If a particle follows the incoming trajectory in the region I, then it crosses the horizon $\bar{U} = 0, V > 0$, which separates the region I from region II. In this case the point $A'$ accounts for an event that happens just before the particle reaches the horizon. Alternatively, one can describe the incoming classical trajectory as the one that leads from the region III to region II. In that case the point $A'$ shows the event that precipitates the crossing of the horizon, which is located at $V = 0, U > 0$. This description is in line with the fact that the motion on the Kruskal plane takes place “from bottom to top” [34].

In order to describe this motion one should choose appropriately a variable for the physical time. In the region I the time can be described conventionally, with the help of the variable $t$. In contrast, the physical time in the region III should be described by the variable $\hat{t}$, where $\hat{t} = -t$.

The described properties of the Kruskal plane have an important consequence. Since two points $A$ and $A'$ on the Kruskal plane describe one and the same event in the physical world, the wave function in these two points must have the same, up to a phase factor, value

$$\phi(A) = \exp(-i\alpha)\phi(A').$$

where notation $\phi(A) \equiv \phi(r,t)$ is used, and the phase $\alpha$ does not depend on $A$. Equation (5.6) represents a simple, but important symmetry condition related to the quantum properties of propagation in the Schwarzschild geometry. Its origin can be traced to the fact that the full coordinate system necessarily double-covers the Schwarzschild geometry. The Kruskal coordinates provide a simple way to implement this fundamental property, though in deriving the symmetry condition Eq. (5.6) one may rely on any other full system of coordinates.

Let us return now to a set of three points $A, A', A''$ shown on the Kruskal plane in Fig. 1, among them $A$ is the initial point, while $A''$ appears after the complex transformation of the variable $r$. This transformation leaves the time variable $\hat{t}$ intact, therefore at the point $A''$ we have $\hat{t}'' = t$. Having in mind the symmetry con-
dation Eq. (5.6), it is desirable to transform the point $A''$ into $A'$. This transformation amounts simply to the inver-
sion of time because at the point $A'$ we have $t' = -t''$
(this inversion of time is in line with the property of the
physical time $\tilde{t} = -t$ discussed above). The time inver-
sion presumes the complex conjugation of the wave
function.

Returning now to Eq. (5.3) one observes that its left-
hand side includes the wave function $\tilde{\phi}(r)$, which can be
associated with the event that takes place at the point
$A''$. The complex conjugation of this function in Eq. (5.3)
gives another wave function, the one that is associated
with the event that happens at the point $A'$ on the
Kruskal plane. The symmetry condition Eq. (5.6) vali-
dates the identity between this later wave function and
the initial wave function, which describes the event at
the point $A$.

In conclusion, the discrete symmetry of the
Schwarzschild geometry combined with conventional
analytical properties of the wave function validate the
RH.

VI. ESCAPE EFFECT

It is convenient to generalize notation in Eq. (2.1), pre-
senting the wave function of a particle in the form

$$|\psi\rangle = |\text{in}\rangle + R |\text{out}\rangle. \quad (6.1)$$

The first term here describes the wave function that has
a conventional, incoming behavior in the vicinity of the
horizon. The second term is a wave that has an un-
expected, outgoing behavior on the horizon. The argu-
ments discussed above verified Eq. (6.1) for the outside
region.

Importantly, this equation remains valid for the inside
region as well. The proof of this later claim given in
[21, 22, 23] goes along the following lines. First one
recovers the time-dependence of the wave function in
Eq. (2.1) by simply multiplying it by a factor $\exp(-i\epsilon t)$,
 i.e. writing $|\psi\rangle \equiv \psi(r) \exp(-i\epsilon t)$. Then one uses the
Kruskal variables Eq. (5.4), (5.5) that allow one to present
this wave function on the horizon more conveniently, as

$$|\psi\rangle = \exp[-i\epsilon \ln(V^2)] + R \exp[i\epsilon \ln(U^2)]. \quad (6.2)$$

The crossing of the horizon between, for example, regions
I and II corresponds to the change of sign of $U$, see Fig.
4. Obviously, this change does not affect the general
structure of the wave function in Eq. (6.2) that is even in
$U$ and $V$. This fact makes the methods of derivation of
Eq. (6.1), which were used above for the outside region,
applicable for the inside region as well.

This discussion justifies the fact that the wave func-
tion always, including the inside region, has an admix-
ture of the outgoing wave. For particles confined inside
the horizon Eq. (6.1) results in a new, unexpected and
interesting phenomenon. Conventional arguments state
that a particle that comes inside the horizon would stay
inside forever because all classical trajectories for this
particle eventually lead to the singularity at $r = 0$. In
quantum description these incoming trajectories corre-
spond to the first term in the wave function in Eq. (6.1),
which gives the incoming behavior in the vicinity of the
horizon. However, the second term in the wave function
gives the outgoing behavior on the horizon. In the clas-
sical description this term corresponds to those classical
trajectories that lead from the singularity at $r = 0$ into
the outside world. The presence of the two terms in the
wave function means therefore that the events that de-
scribe the incoming particle are necessarily mixed in the
wave function with the events that describe the outgoing
particle, as was found in [21, 22, 23]. Simply speaking,
the particle confined inside the horizon has a chance to
escape into the outside world. We call this the escape
effect (EE).

A. Hawking radiation

Conventional qualitative explanation for the Hawking
effect refers to the virtual particle-antiparticle pairs that
exist in the vicinity of the horizon due to quantum fluc-
tuations. The strong gravitational field on the horizon is
able to separate the pair, bringing one of its components
inside the black hole, and allowing the other component
to go outside and constitute the flux of outgoing radia-
tion.

The EE provides a different, appealing explanation of
the radiation phenomenon. The radiation happens
due to the fact that a particle locked inside the horizon
can escape from the confinement into the outside world,
creating the flux of outgoing radiation. The EE is en-
tirely related to the second term in the right-hand side
of Eq. (6.2). Accordingly, the probability that a particle
escapes into the outside region is governed by a factor $P$,

$$P \propto |R|^2 = \exp \left( -\frac{\epsilon}{T} \right), \quad (6.3)$$

which looks similar to the probability of the Hawking ra-
diation. However, to make this similarity complete, one
has to presume that The distribution of particles inside
the event horizon is governed by the same Hawking tem-
perature. This condition is satisfied when a black hole is
put inside the temperature bath, which has the Hawking
temperature. This formulation of the problem was dis-
cussed by Hartle and Hawking [30]. The analysis in [22]
shows that for this particular case the flux of radiation
that appears due to the EE reproduces the spectrum of
a black body with the Hawking temperature.

B. Escape of particles and information transfer
from the inside region

Conventionally it is presumed that an outside observer
can measure only few characteristics of the black hole,
such as its mass, spin and charge. All other information related to the collapsing matter that created the black hole is supposed to be screened from the outside observer by the event horizon. Thus, presumably the collapse produces large information loss.

However, the wave function Eq. (6.2) indicates that there is the EE, which provides a chance to retrieve the information from within the horizon back into the outside world.

To be specific, consider a situation when the usual matter (made of electrons, protons etc) collapses producing a black hole. Conventionally it is supposed that for the outside observer this black hole would not look different from a black hole made from the antimatter (positrons, antiprotons etc). However, the discussion in Section VI.A indicates that the radiation of black holes takes place due to the EE. If the black hole is made of matter, then there are only electrons inside, but there are no positrons. In this case the outside observer would be able to see the flux of electrons, which escape from the inside region, while there would be no positrons in this spectrum. From this fact the observer concludes that the black hole is made from conventional matter. Similarly, the outside observer is able to detect other signals that correspond to other characteristics of the collapsed matter, thus retrieving the information hidden inside the horizon.

At this point it is instructive to return back and compare the EE with the phenomenon of the Hawking radiation. There are some similarities. In both cases there is a flux of radiation due to processes that take place on the horizon, in both cases the exponential function of the ratio of energy to the Hawking temperature is present. However, there are serious distinctions. The Hawking process is often explained via the pair production on the horizon. This usual and clearly looking physical picture possesses, though, an intrinsic difficulty. The component of the pair that goes inside the horizon should possess the negative energy. This is the only way that allows the black holes to reduce its mass in the process. This negative energy of the ingoing particle equals $\varepsilon_{\text{in}} = -\varepsilon$, where $\varepsilon > 0$ is the positive energy of the outgoing particle. The point is that $\varepsilon_{\text{in}}$ is supposed to be the total energy of the ingoing particle, the energy which is conserved, being equal therefore the energy that a particle would possess when located far outside of the black hole. This energy should definitely be positive. Admitting that it is negative, one makes an assumption, which introduces a difficulty into this physical picture of the Hawking radiation.

The EE does not have this problem. The EE states that a particle is able to escape over the horizon. During this process its positive energy remains intact. Obviously, when a particle is left, the mass of the black hole becomes smaller. There is no need in this physical picture to introduce negative energies.

Another important feature that distinguishes the EE from the Hawking radiation is the actual spectrum of a black hole. For the EE process it is not governed by the temperature. The temperature, as it appears in Eq. (C.3) is a parameter that has only limited applicability, describing the probability of the escape of the particle from the inside region. But the flux of the outgoing particles depends also on the probability that particular particles exist inside the horizon. In other words, if there is some particular type of particles inside the horizon, then these particles can escape, giving a contribution to the radiation spectrum. Accepting this “limited” point of view on the temperature, one should, probably, also modify the point of view on the entropy and the thermodynamic properties of black holes, but we do not elaborate on this argument here leaving it for further considerations.

VII. CONCLUSION

The central point of the presented discussion is the claim of Refs. 21, 22 and 23 that the wave function of any particle that approaches a black hole has an admixture which possesses unusual properties, describing the outgoing wave on the horizon. This important property originates from pure quantum reasons. In the classical approximation all trajectories cross the horizon smoothly, leaving no opportunity for a particle to switch from the incoming to outgoing trajectory. Following the incoming trajectories all particles inevitably end up in the singularity at $r = 0$. In contrast, on the quantum level the incoming and outgoing waves are mixed in the wave function on the horizon. Thus, it is impossible to describe the particle in terms of the wave that has only incoming component on the horizon.

The existence of the outgoing wave on the horizon has important and unexpected implications. One of them is related to the scattering problem. Any particle approaching the black hole can bounce on the horizon back into the outside world. The corresponding effect, called the reflection on the horizon, drastically reduces the absorption cross section in the infrared region 24.

Another notable phenomenon takes place for the collapsed matter that is confined inside the event horizon. Classically such confinement is absolute, there is no way for a particle to return into the outside world. The quantum treatment shows that there is such a chance, a particle can escape. This opportunity was called the escape effect. The probability that some particle gets away is governed by the exponential factor, which looks very conventional, being dependent on the ratio of the energy of the particle to the Hawking temperature. Due to this reason the flux of escaping particles resembles the spectrum of the Hawking radiation. This similarity turns into identity when we consider a black hole that is placed inside the temperature bath.

However, in the general case the spectrum of the escaped particles depends also on properties of the col-
lapsed matter. As a result the flux of the escaped particles brings the information from the inside region into the outside world. This important fact may, probably, help resolve the information paradox. We did not attempt to prove in this work (or in the previous ones [21, 22, 23, 24]) that all the information about the collapsing matter can be retrieved from under the horizon. However, the escape effect definitely allows some information to be recovered. The implications of this fact may be far reaching, prompting, probably, a new look on thermodynamics properties of black holes.

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[31] Note, however, that the simple mechanism of the pair production possesses a difficulty, as is discussed in some detail in Section [718] below. At this point, however, we stick to the conventional point of view, neglecting this complication in order to present the RH in the commonly used terms.
[32] In deriving this result, the continuation over the lower semiplane of the complex plane r was used. If one applies a different analytical continuation, over the upper semiplane, one ends up with the large reflection coefficient |R| ≥ 1 that is physically unacceptable. This fact can be used as an indication that the chosen way for the analytical continuation is correct. Detailed validation of analytical properties of the wave function should be based on the causality condition, but we do not go into these details here, see more on the subject in [21, 22, 23].
[33] This procedure resembles partially the method discussed in Section [741] where we applied similar rotation on the complex plane. However in Section [741] the angle of rotation was chosen π, which brought r into the inside region r < 1. In contrast, the 2π rotation discussed here ends up with r returning into the outside region r > 1.
[34] Generally speaking, other identifications between the regions I and III are possible, see Refs. [28, 29]. However, the identification discussed here is most common, it is in line with the book [27].
[35] Assuming that during the collapse the temperature of the matter remained sufficiently low for production of the antimatter in large quantities.
[36] This difficulty was a driving force that prompted the studies in [21, 22, 23].