The principle and state-of-art applications of Hawking radiation

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Abstract—Hawking radiation, firstly discovered in 1974 by Stephen Hawking, is a crucial quantum phenomenon, which proves that a black hole has been losing its mass since its formation. In this paper, the method of information retrieval and literature analysis are fully applied to introduce the principle and state-of-art applications of Hawking radiation. Three parameters used to describe the evaporation of black holes are analyzed. Furthermore, the tunnelling effect of entangled pairs near event horizon is described to explain Hawking radiation from a microscopic perspective. Then, the evaporating black holes are observed under wave optical conditions by the Fourier transformation of the spatial correlation function and detected in Laboratory condition by equivalenting entangled pairs to surface wave packets with sum-zero energy. Finally, a prediction is made that the widely used of extra-dimensional theory and high-energy particle technology as well as numerical researches in laboratory conditions will be strongly pushing the observation of Hawking radiation. Overall, these results shed light on further exploring the universe in terms of Hawking radiation.

1. INTRODUCTION

Hawking radiation is an important quantum phenomenon proposed by British physicist Stephen Hawking in 1974, which makes a prediction that black holes produce thermal radiation [1]. According to general relativity, a black hole absorbs everything but emits nothing. In other words, it is a region of space that nothing (even the photons), can escape from its interior because of the intensive gravitational field [2]. However, this hypothesis cannot be explained by conventional quantum mechanics theories. As Hawking discovered, black holes should behave similar to black bodies and thus emit thermal radiation with temperatures proportional to their surface gravities on the event horizons. According to Hawking's calculations, thermal radiation is only significant for so-called quantum black holes, whose size is smaller than that of an atomic nucleus [3].

In order to improve the Hawking radiation theory, plenty of approaches are proposed and many appealing research results have been demonstrated. Gibbons and Hawking's research gives the temperature formular for Hawking radiation calculation. However, they questioned that it is unknown whether an event horizon associated with some dynamical spacetime at a given time exists or not, which poses a great difficulty in discussing Hawking radiation for dynamical black holes [4]. Hayward derived a local Hawking temperature for dynamical black holes and defined the Killing value to reflect measurements at infinity. In Newtonian limit, the geometrical surface gravity is converted to the Newtonian surface gravity, which may settle a longstanding problem about the Hawking temperature of the charged stringy black hole for the extremal limit [5].

Although the existence of Hawking radiation has not been observed yet, Hawking's quantum gravity theoretical model has become the basis of many studies in physics and cosmology. Singh's research revealed the Generalized Uncertainty Principle (GUP) effect of Baados-Teitelboim-Zanelli (BTZ) black holes by using Hamilton-Jacobi method and Dirac equation. Damour and Ruffini method, tortoise coordinate transformation and modified Klein-Gordon equation were used to modify Hawking radiation of massless particle from a BTZ black hole. The relation between the modified Hawking temperature and the energy of the emitted particle is deduced [6]. Zeng discussed the information missing puzzle in Hawking radiation. It proved that Hawking's neglecting or implicit averaging over the inner structure microstate of black holes leads to the information missing puzzle. Meanwhile, a semi-classic fuzzy ball picture for microstate of black holes and a Hamiltonian thus explicitly unitary formulation for Hawking radiations are proposed to make the various information missing argument in Hawking radiations easy to resolve [7].

Hawking's quantum black holes theoretical model resolves the contradictions existing in the black hole thermodynamics, reveals the connection between gravity theory, thermodynamics, and quantum theory. The rest part of the paper is organized as follows. The Sec. II gives basic descriptions of Hawking radiation, introducing a calculation model of Hawking temperature and the meaning of variables used in the model. The Sec. III lists several applications of Hawking radiation, especially in cosmology and thermodynamics. The Sec. IV points out the limitations of Hawking radiation theory in quantum mechanics while gives a preview of researches in this field. Eventually, a brief summary is given in Sec. V.

2. Basic Descriptions of Hawking Radiation

Hawking radiation theory explains the reason that black holes have continued to losing mass since their formations. There are three important parameters to describe this process as discussed following.

2.1.Hawking temperature

Hawking temperature is an important parameter to calculate thermal radiation. It represents the surface temperature of a black hole. In Unruh effect, a relationship between vacuum temperature T and observer's acceleration a can be derived. By placing the particle trajectory in Schwarzschild horizon into geodesic equation, the Hawking temperature T_H in Rindler coordinates is deduced. Eq. (1) shows the way to calculate the Hawking temperature T_H of a black hole massed M_{BH}. All the parameters are constants, i.e., makes this formular so concise, which clearly indicates that the mass of black holes and the radiation temperature are in inverse proportion. The mathematical description can be described as follows:

$$T_H = \frac{hc^3}{8\pi kGM_{BH}} \tag{1}$$

where h, c, k, G represent the Planck constant, the speed of light in vacuum, Boltzmann constant and gravity constant, respectively [8]. According to Eq. (1), the Hawking temperature is proportion to the mass of the black hole.

2.2.Bekenstein-Hawking Luminosity

Bekenstein-Hawking luminosity is used to calculate thermal radiation power. Based on Eq. (1), the hawking temperature on the surface of the sun can be calculated. Subsequently, in terms of Wien displacement law, the maximum radiation wavelength of sun surface can be deduced:

$$P = \frac{hc^6}{15360\pi G^2 M_{BH}^2} \tag{2}$$

In Eq. (2), parameters are the same as Eq. (1) which holds on blackbody assumption [9].

2.3.Evaporation Time

The evaporation time of a black hole can be calculated by Eq. (3),

$$t_e = \frac{5120\pi G^2 M^3}{hc^4} \tag{3}$$

in which parameters have the same numerical value as Eq. (1) and Eq. (2). It could be estimated that the evaporation time of a black hole with the same mass as the Sun ($M_{sun} = 2 \times 10^{30} kg$) is about 10^{67}years [10].

3. Application of Hawking Radiation in Observing Black Holes

Hawking radiation is thermal radiation, which proves that black holes are releasing energy continuously. This process is called the black hole's evaporation. It can be inferred that black holes evaporate away completely eventually. However, this process is so slow that a black hole with mass of 10^{12}kg, has been evaporating since the early universe. Fig.1 describes different stages of process of the black hole's evaporation.

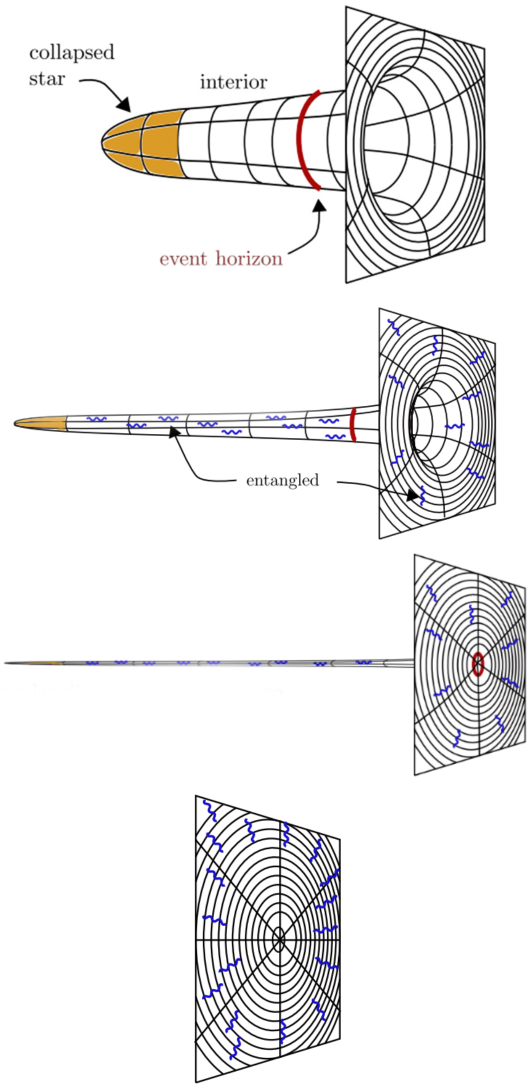

Figure 1. A sketch of different Stages (Stage 1 to 4 from upper panel to lower panel) of black hole's evaporation [11]. Stage.1, the inside of the black hole continues to elongate when stellar collapse.

Stage.2, one's escaping to infinity is observed as radiation after generation of entangled pairs. Stage.3 the angular directions shrink to zero size, becoming the singularity eventually. Stage4, the black hole's evaporation is completed at the end.

The process of evaporation can be described as 4 stages as illustrated in the Fig. 1. At the first stage, the space within in a certain distance from a collapsed star, which is called event horizon, continues to elongate in one direction, while the space out of event horizon is nearly stationary. At the second stage, according to Heisenberg Uncertainly Principle, entangled pairs continue to be created in vacuum. Under the great gravity in this space, one particle escapes to infinity while the other is trapped inside event horizon, which is observed as blackbody radiation. At the third stage, when the black hole almost evaporates to one point, the angular directions shrink to almost zero size. At the last stage, the black hole completely evaporates and disappears.

Investigation of Hawking radiation can help deepen human's understanding of black holes. In general relativity, a black hole is a bounded spacetime, where the gravity is so great that almost nothing captured by the gravitational of black hole can escape to the null infinity, which makes black holes difficult to be observed in optical field. The bound is called the event horizon. For a distant observer, the space distortion makes a set of photon orbits are observed as a distorted disk on a far observer's view plane. By detecting a black hole's Hawking radiation from a far distant, the wave optical images of the evaporating black hole can be reconstructed.

Assuming that there are two detectors placed near the cosmological horizon in a spherical coordinate system, the reflection and transmission coefficients in the upper detector are demonstrated in the three pictures above of Fig. 2. While the same parameters of the lower detector in Schwarzschild case are shown in the lower panel of Fig. 2 [12]. A superimposed image of black hole with the vacuum fluctuation in the UP mode is exhibited in Fig. 3. The photon sphere in geometric optics has a finite width shape in wave optics. The black hole has the appearance of a shining star and with a surface coinciding with the photon sphere.

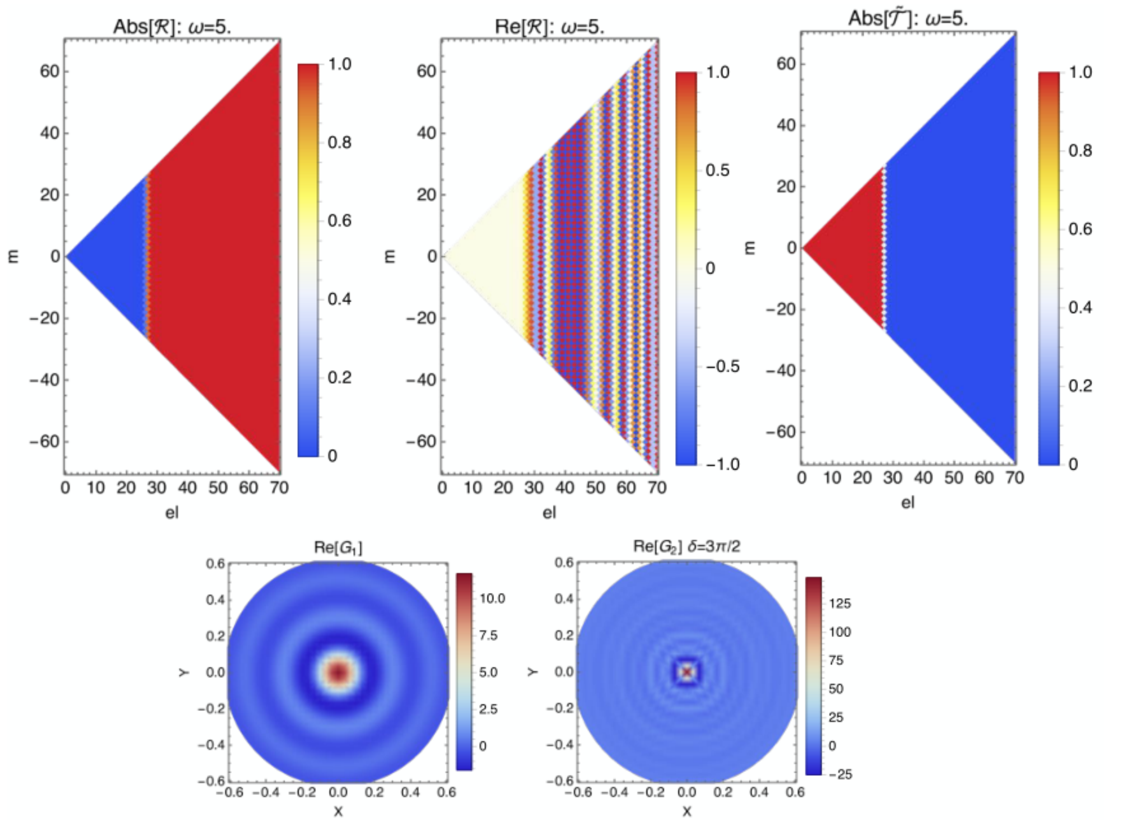

Figure 2. Reflection and transmission coefficients in Schwarzschild horizon [12].

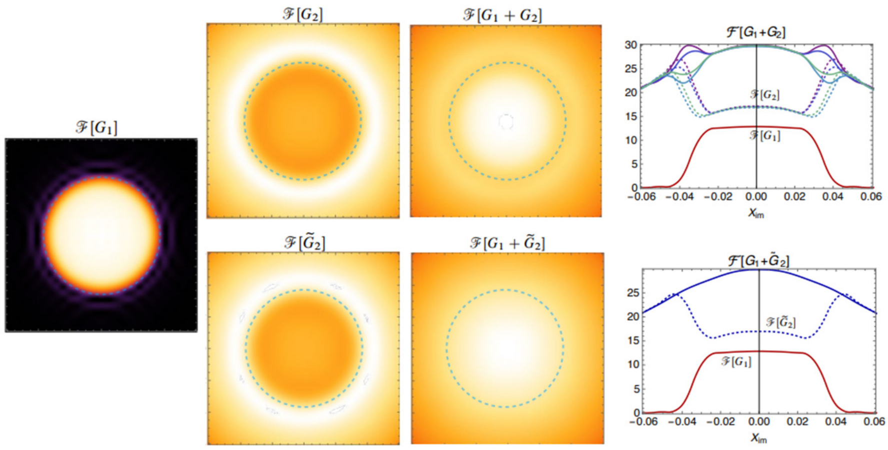

Figure 3. Images obtained by the Fourier transformation of G [12].

4. Detection of Hawking Radiation in Laboratory Analog

To detect some key properties of surface Hawking radiation of non-rotating black holes under laboratory conditions, two surface gravity wave pockets are selected, which are commonly used in the study of particle scattering problems. The surface gravity wave pockets with opposite energy but the same amount of wave action is used to simulate entangled pairs. Created out of near horizon vacuum fluctuations, entangled pairs consist of two particles. The virtual particle pairs with opposite energy are simulated by a minimal water wave model. In vacuum fluctuations near the black hole, the particle with positive energy escape to infinity, while the other falls in to the black hole, leading to black hole evaporation.

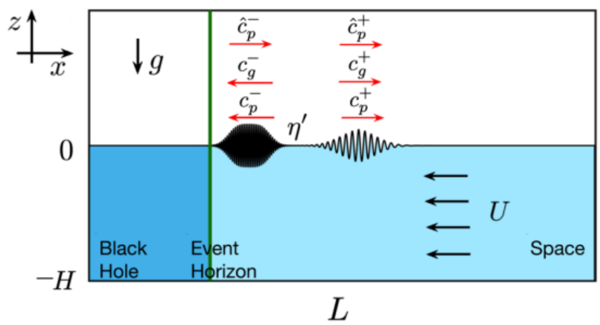

Figure 4. Schematic diagram of the entangled pairs simulated by surface gravity wave pockets [13].

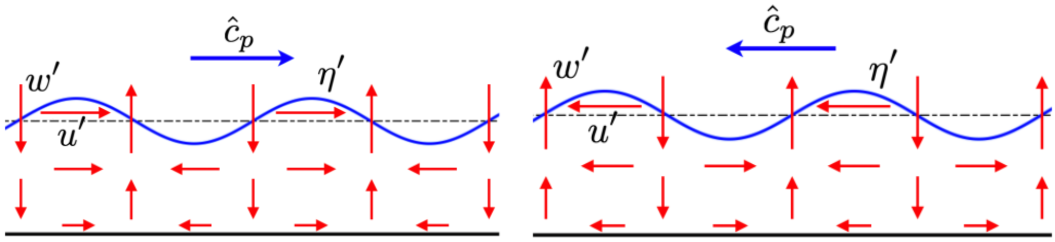

Figure 5. Schematic diagram of the pseudo-momentum of the pairs of wave packets [13].

Superposition pairs of wave packets with opposite values of pseudo-energy are chosen to ensure that the entangled pairs can be represented by them. Fig. 5 depicts that the two paired packets have opposite pseudo-momentum when the system has a tiny disturbance. It indicates that the two paired packets have opposite moving direction, performing the same with entangled pairs formatting in space near a black hole (seen from Fig.6).

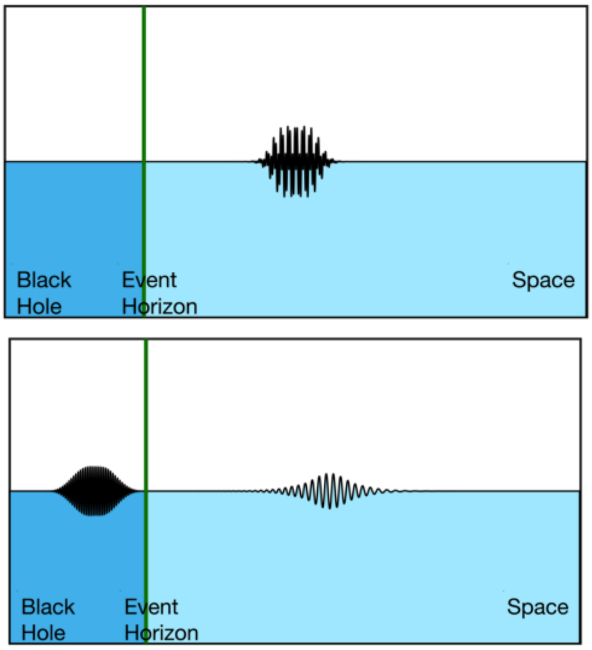

Figure 6. Simulation of sum-zero pseudo-energy packet [13].

5. Limitation & Future prospects

The existence of Hawking radiation has not been actually observed yet. As a great curved space-time quantum field theory, it ignored the internal contradiction of general relativity and quantum mechanics forcibly integrated together. However, there will be some irreconcilable limitations in Hawking radiation theory when the horizon gradually narrowed to a certain scale.

Nevertheless, Hawking radiation theory is a reasonable explanation of quantum gravity theory, explaining the path that the mass of a black hole is reduced and the reason for black holes' evaporation. Meanwhile, the reliability of detecting Hawking radiation by using surface gravity wave pockets will be demonstrated further through numerical simulation on the nonlinear effects of wave dissipation and wave mean flow interaction in laboratory conditions. In addition, the applications of extra-dimensional theory and high-energy particle collision experiments may create temporary micro black holes emitting radiation of specific wavelengths, which may allow Hawking radiation to be observed firstly in laboratory in the future.

6. Conclusion

In summary, this paper discusses the principle and state-of-art applications of Hawking radiation. Based on the analysis, Hawking's quantum black holes theoretical model builds the connection between gravity theory, thermodynamics, and quantum theory, which firstly proves that black holes keep losing mass since their formation. Hawking radiation theory is widely used in researches in cosmology and thermodynamics. In the future, abundant studies in theoretical and experimental will promote human's proof of Hawking radiation theory. Overall, these results offer a guideline for understanding the basic law of Hawking radiation theory and its significance to the study of black holes.

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