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Information-carrying Hawking radiation and the number of microstate for a black hole

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Abstract

We present a necessary and sufficient condition to falsify whether a Hawking radiation spectrum indicates unitary emission process or not from the perspective of information theory. With this condition, we show the precise values of Bekenstein–Hawking entropies for Schwarzschild black holes and Reissner–Nordström black holes can be calculated by counting the microstates of their Hawking radiations. In particular, for the extremal Reissner–Nordström black hole, its number of microstate and the corresponding entropy we obtain are found to be consistent with the string theory results. Our finding helps to refute the dispute about the Bekenstein–Hawking entropy of extremal black holes in the semiclassical limit.
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1. Introduction

In the earlier 1970s, black hole thermodynamics were established based on the analogies between the laws of black hole dynamics and thermodynamics [1–7]. With this arises two open questions, the information loss paradox and the puzzled origin for a black hole's entropy. When quantum theory is applied to a black hole, Hawking discovered a black hole radiates and the so-called Hawking radiation is approximately thermal [6,7]. Since thermal radiations do not carry correlations, the discovery of Hawking radiation leads to the famous claim that information about the collapsed matter in a hole is lost [8,9]. Recently, we present a plausible yet consistent resolution for the black hole information loss paradox, in a series of studies [10–13] with collaborators. At the heart of our work is the discovery of correlations among Hawking radiations [14–17] when the emission spectra takes the nonthermal form of Parikh and Wilczek [18].

The concept of entropy is not only used in information theory, it is a relevant concept also in thermodynamics, where the precise value for the entropy of a system is determined by the number of its microstates [19]. The existence of information default, or an amount of information unreachable to an observer, is the origin for a black hole's entropy. The nonzero entropy for a black hole implies the lack of information about the collapsed matter in a hole for an observer outside the hole. A long-standing conjecture relates the entropy of a black hole to its microstates near event horizon [20–23]. Bekenstein estimated it for a Schwarzschild black hole by considering the change of its horizon surface area from a falling particle across the horizon forty years ago [4]. Based on information theory, he arrived at the area entropy of a black hole $(\ln 2/8\pi)kc^3A/G\hbar$, where A is the event horizon area of the black hole. Bekenstein's result is almost the same as the standard result $kA/4l_p^2$ given by Hawking, which is obtained based on the thermodynamic relationship between energy, temperature, and entropy [7]. This establishes the entropy of a black hole is proportional to its area at event horizon. The origin of this entropy, however, remains a puzzle until now.

Finding the precise value of the entropy for a black hole from counting its number of microstates near the event horizon represents a daunting task [24]. Accomplishing this goal will shine light on the puzzled origin for a black hole's entropy and implicate the establishment of a successful quantum gravity theory. Serious efforts have been carried out along this direction without too much successes. Most notably, it was found that the entropies for some black holes, such as the five-dimensional extremal black holes can be obtained in string theory by counting the degeneracies of the BPS soliton bound states [25]. An approach based on the correspondence between AdS_3 and conformal field theory was also proposed to count the number of states for the BTZ black hole [26]. Other studies have extended the above calculations to entropies for extremal or near-extremal black holes [27]. With limited exciting progresses made for some types of black holes as mentioned above, the relationship between the number of microstates and the Bekenstein–Hawking entropy remains to be established for non-extremal black holes, including the most commonly discussed Schwarzschild black hole.

This work is focused on counting the microstates of Hawking radiation to recover the Bekenstein–Hawking entropy for a black hole in the semiclassical limit. We first discuss a necessary and sufficient condition capable of falsifying unitary Hawking radiation from the perspective of information theory. The precise values of Bekenstein–Hawking entropies for Schwarzschild black holes and Reissner–Nordström black holes are then calculated by counting the number of microstates of their respective Hawking radiations. For Reissner–Nordström black holes, alternative spectra for neutral or charged Hawking radiation emissions are considered, and based on which the number of microstates for the extremal Reissner–Nordström black hole is counted

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