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The Hawking paradox and the Bekenstein resolution in higher-dimensional spacetimes

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Abstract

The black-hole information puzzle, first discussed by Hawking four decades ago, has attracted much attention over the years from both physicists and mathematicians. One of the most intriguing suggestions to resolve the information paradox is due to Bekenstein, who has stressed the fact that the low-energy part of the semi-classical black-hole emission spectrum is partly blocked by the curvature potential that surrounds the black hole. As explicitly shown by Bekenstein, this fact implies that the gray-body emission spectrum of a $(3+1)$-dimensional black hole is considerably less entropic than the corresponding radiation spectrum of a perfectly thermal black-body emitter. Using standard ideas from quantum information theory, it was shown by Bekenstein that, in principle, the filtered Hawking radiation emitted by a $(3+1)$-dimensional Schwarzschild black hole may carry with it a substantial amount of information, the information which was suspected to be lost. It is of physical interest to test the general validity of the "information leak" scenario suggested by Bekenstein as a possible resolution to the Hawking information puzzle. To this end, in the present paper we analyze the semi-classical entropy emission properties of *higher*-dimensional black holes. In particular, we provide evidence that the characteristic Hawking quanta of $(D+1)$-dimensional Schwarzschild black holes in the large $D \gg 1$ regime are almost unaffected by the spacetime curvature outside the black-hole horizon. This fact implies that, in the large-D regime, the Hawking black-hole radiation spectra are almost purely thermal, thus suggesting that the emitted quanta *cannot* carry the amount of (non-thermal) information which is required in order to resolve the information paradox. Our analysis therefore suggests that the elegant information leak scenario suggested by Bekenstein, which is based on the effective gray-body (rather than a black-body) nature of the black-hole emission spectra, *cannot* provide a generic resolution to the intriguing Hawking information paradox.

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1. The Hawking black-hole information puzzle

The black-hole evaporation phenomenon, first predicted by Hawking [1] more than four decades ago, imposes a great challenge to our understanding of the interplay between gravity and quantum theory. In particular, Hawking's semi-classical analysis [1] asserts that black holes which were formed from the gravitational collapse of pure quantum states will emit thermally distributed radiation and thus eventually evolve into mixed thermal states. This intriguing physical scenario is in sharp contradiction with the fundamental quantum mechanical principle of unitary temporal evolution, which asserts that pure quantum states should always remain pure as they evolve in time [2].

The incompatibility between gravity and quantum physics, which is realized most dramatically in the Hawking evaporation process of black holes, may also be discussed in terms of the fundamental principles of quantum information theory [3]. In particular, it is well known that perfectly thermal (black-body) radiation cannot convey detailed information about the physical properties of its emitting body. Thus, according to Hawking's semi-classical analysis [1], the information hidden in the intermediate black-hole state about the initial quantum state of the collapsed matter is lost forever with the complete thermal evaporation of the black hole. This physically intriguing scenario is known as the Hawking black-hole information puzzle.

2. The elegant resolution suggested by Bekenstein

Several physical scenarios have been suggested in order to resolve the Hawking black-hole information puzzle, see e.g. [3–5] for excellent reviews. In the present paper we would like to analyze a particular intriguing resolution originally proposed by Bekenstein [3]. The possible solution suggested by Bekenstein [3] to the Hawking information paradox [1] belongs to the family of "information leak" scenarios. According to this suggested resolution, the information about the initial quantum state of the collapsed matter, which is supposed to be lost during the semi-classical Hawking evaporation process, is actually encoded into the emitted black-hole radiation quanta [3].

Specifically, Bekenstein [3] has correctly pointed out that, due to the effective curvature potential that surrounds the emitting black hole, the Hawking radiation spectrum of a $(3+1)$-dimensional Schwarzschild black hole departs from the familiar purely thermal radiation spectrum of a perfect black-body emitter. In particular, the characteristic curvature (scattering) potential of the black-hole spacetime [see Eq. (10) below] partly *blocks* the low-frequency part of the semi-classical Hawking emission spectrum. The departure of the black-hole radiation spectrum from the purely thermal spectrum of a perfect black-body emitter can be quantified by the dimensionless energy-dependent gray-body factors $\{\Gamma(\omega)\}$ [6] of the composed black-hole-radiation-fields system. In particular, the low-frequency part of the semi-classical black-hole radiation spectra is known to be characterized by the simple limiting behavior [6][1]

$$\Gamma(\omega r_{\text{H}}) \to 0 \quad \text{for} \quad \omega r_{\text{H}} \to 0\,. \tag{1}$$

[1] Here r_{H} is the horizon radius of the emitting black hole.