論文の内容の要旨

論文題目 Entropy of Hawking radiation in entangled disjoint universes and the island formula

(エンタングルした分離宇宙におけるホーキング放射のエントロピーとアイランド公式)

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The black hole information paradox is one of the most important problems in quantum gravity. It argues that in a system where a black hole is emitting Hawking radiation, the semi-classically calculated von Neumann entropy of the Hawking radiation exceeds the Bekenstein-Hawking entropy of the black hole, leading to the inconsistency with the quantum gravity. The paradox plays a very important role in the understanding of quantum gravity. One of the expected results from quantum gravity is Page's discussion using a toy model [1]. The discussion leads to the behavior that the von Neumann entropy of Hawking radiation increases up to a certain time, which is called the Page time, and then decreases or remains unchanged after the time. Such a behavior of the von Neumann entropy is known as the Page curve. The challenge of how to obtain a von Neumann entropy that follows the Page curve using a semi-classical gravitational calculation is very important for addressing the black hole information paradox.

Recently, the development of the understanding of the calculation method of von Neumann entropy in the AdS/CFT correspondence, such as Ryu-Takayanagi formula, has revealed that the von Neumann entropy following the Page curve can be obtained by using the so-called island formula. This island formula can reproduce the post-Page behavior of the Page curve, in addition to the pre-Page behavior, by appropriately considering the contribution of a region called the island in the interior region of a black hole. Therefore, we should further understand this island formula because it plays a very important role in understanding the black hole information paradox and furthermore in understanding the interior structure of black holes.

In this thesis, we focus on the island formula and study it from two perspectives.

The first one is to apply a setup called the disjoint setup to a black hole in (asymptotically) flat spacetime, based on our paper [2]. The disjoint setup can be considered as an idealization of the situation where a black hole is emitting Hawking radiation. To be concrete, consider two universes, one without gravity, the other with gravity and a black hole, where the matter states on those universes are entangled with each other. Intuitively, one can imagine that this situation is made by collecting Hawking quanta emitted from the black hole and sending them to the non-gravitating universe. While the previous works [3, 4] studied the case of black holes in anti-de Sitter and de Sitter spacetimes, in this thesis, we focus on the case of black holes in (asymptotically) flat spacetimes, as described above, and study them by using the island formula.

In the disjoint setup, we consider the entanglement state between the two universes, corresponding to the entanglement between Hawking radiation and the black hole, the existence of the entanglement plays a very important role in the existence of the island. To understand this further, we consider operations on the gravitating universe to change the entanglement slightly. Such an operation is modeled by the so-called local quench, by which we insert a local operator into the gravitating universe, and we calculate the von Neumann entropy under the situation. The results show that the behavior of the Page curve in the disjoint setup changes depending on the position of the local operator. In particular, we observed that the change in the behavior of the Page curve can be interpreted as an acceleration of the evaporation process of the black hole in the disjoint setup.

Second, based on our paper [5], we reconsider the treatment of the ensemble of quantum states that appears in semi-classical description of a black hole by introducing new degrees of freedom, which we call the baby universe, and discuss the relation between the island formula and the baby universe. By appropriately treating such a new degree of freedom, it is possible to obtain the von Neumann entropy consistent with the Page curve and also the island formula. We also discussed some implications of the introduction of the baby universe. For example, it was pointed out that gravitational dressing for operators inside a black hole usually leads to a paradox [6], but the introduction of the new degree of freedom allows us to avoid such a paradox.

References

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