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研究課題名（和文）Black Holes, Quantum Physics and Holography

研究課題名（英文）Black Holes, Quantum Physics and Holography

研究代表者

Ｈｏｓｓｅｉｎｉ　ＳｅｙｅｄＭｏｒｔｅｚａ（Hosseini, Seyed Morteza）

東京大学・カブリ数物連携宇宙研究機構・特任研究員

研究者番号：９０８２２１０６

交付決定額（研究期間全体）：（直接経費）　　2,800,000円

研究成果の概要（和文）：弦理論での種々のブラックホールの微視的状態を同定し、そのエントロピーを巨大ブラックホールの場合のベケンスタイン=ホーキングエントロピーだけでなく、さらなる補正項も含め精密に決定するため、数学的な新たな手法を用い、種々の次元の場の量子論の厳密な分配関数や相関関数を計算した。
その際アンチドジッター(AdS)時空における量子重力の非摂動的定式化が共形場理論(CFT)によって与えられているという観点が重要になるため、新たな例を構成した。

研究成果の学術的意義や社会的意義
この研究は、アンチドジッター時空におけるブラックホールの量子力学的振舞、とくにその微視的起源を解明することが目的であり、これは素粒子理論、一般相対論、数学の三分野の交わる先端かつ境界の領域である。研究代表者の発表した論文はすでに合計三百回以上引用されており、ブラックホールの量子物理の研究の新機軸を開いてきた。これを元に、今後はブラックホールに関するさらに深い問題を研究することができるようになる。

研究成果の概要（英文）：My research project aims at identifying the quantum microstates of different classes of black holes in string theory and giving a precise derivation of their quantum entropy -- the Bekenstein-Hawking entropy is just the leading approximation to the quantum black hole entropy for large black holes and receives infinite series of finite-size corrections. I developed new mathematical tools and methods in understanding the quantum nature of black holes. These include computing the exact partition functions and correlation functions of quantum field theories in various dimensions.
Moreover, the AdS/CFT correspondence provides a non-perturbative definition of quantum gravity in AdS spacetimes. I gave various evidence for this idea, via constructing new examples, and used it to understand both quantum field theories and quantum gravity.

研究分野：String theory

キーワード：AdS/CFT Correspondence　Black holes　Supergravity models　Supersymmetry

１．研究開始当初の背景

Once viewed as fictional objects, black holes are now firmly rooted in reality, after recent detections of their mergers and imaging of their horizon. Nonetheless, they continue to raise many theoretical puzzles. As understood by Bekenstein and Hawking in the mid 70s, black holes carry an entropy equal to one quarter of the area of their event horizon measured in Planck units. This quantity satisfies the same principles as the usual entropy of thermodynamic systems, and it is natural to ask if it has a microscopic origin a la Maxwell-Boltzmann. On the other hand, there is an obvious tension between the fact that the entropy of a thermodynamic system is usually proportional to its volume while the black holes entropy is proportional to the area of its event horizon. As shown by Maldacena in late 90s, this is resolved by the holographic principle, which in its most basic form equates gravitational physics in a finite region with ordinary quantum field theory (QFT) on its boundary. In particular, the entropy of black holes in a finite region of space should be related to the number of ground states in the dual QFT living on its boundary.

The holographic principle maps weak curvature to strong coupling, so questions about macroscopic black holes require non-perturbative techniques on the field theory side. The latter is usually described a la Feynman by a functional integral over all possible field configurations in Euclidean spacetime, which is hard to compute except for Gaussian free theories, or topological field theories on compact manifolds, such as Chern-Simons theory. For supersymmetric field theories the localization principle allows one to reduce the infinite-dimensional functional integral into a finite-dimensional integral, called matrix model, and compute some exact results for supersymmetric observables in strongly coupled QFTs. Combining the ideas of localization and holography, can thus give very precise predictions for the quantum gravity.

The holographic principle is rooted in String theory, which seems to be the prime candidate for a consistent theory of quantum gravity. While not yet validated experimentally, string theory offers a good testing ground for exploring the quantum nature of black holes, thus helping us to answer questions that would be yet impossible to attack otherwise. In particular, Strominger and Vafa in their groundbreaking work, have demonstrated the viability of string theory by providing a microscopic interpretation for the Bekenstein-Hawking entropy of certain classes of black holes in asymptotically flat spacetimes. This striking success has been achieved by representing black holes as bound states of branes and strings, that are microscopic constituents of string theory. All these developments have culminated in the formulation of a concrete and quantitative example of the holographic principle, namely the anti de Sitter/conformal field theory (AdS/CFT) correspondence. This is the key success to the recent progress in understanding black holes puzzles, especially deriving the macroscopic entropy of black holes in asymptotically AdS spacetimes. In this picture, black holes are thermodynamical ensembles of microstates in a holographic dual CFT.

After the invention of the AdS/CFT correspondence, the search for microstates of black holes in asymptotically AdS spacetimes has become paramount. While many AdS black holes in various dimensions have been constructed in the last twenty years, it is only very recently that Benini, Hristov, Zaffaroni could explain the microscopic origin of a class of magnetically charged AdS black holes in four dimensions. I built upon this impressive result and extended their computation to other matrix models. My articles have already opened new lines of research in studying the black holes physics and I plan to continue this research so as to reach a precise and quantitative identification of black hole microstates in AdS and more general spacetimes. The JSPS KAKENHI Grant-in-Aid (Early-Career Scientists) will allow me to pursue my objectives with the help of talented researchers.

２．研究の目的

My research proposal aims at investigating the quantum properties of black holes in AdS spacetimes, especially identifying the microscopic origin of their entropy. This is a very difficult problem, at the frontiers of high energy theoretical physics, general relativity and mathematics. The ultimate goal of my research is to resolve the long-standing puzzles surrounding black holes such as the information paradox, and to uncover hidden features of a consistent theory of quantum gravity.

Objectives

i) Identifying the quantum microstates of different classes of black holes in string theory and giving a precise derivation of their quantum entropy

ii) Developing new mathematical tools and methods in understanding the quantum nature of black holes. These include computing the exact partition functions and correlation functions of QFTs in various dimensions.

iii) The AdS/CFT correspondence gives a non-perturbative definition of quantum gravity in AdS spacetimes. I provide various evidence for this idea, by constructing new examples, and use it to understand both QFTs and quantum gravity. If this line of research can be extended to spacetimes beyond AdS this will lead to a breakthrough in our understanding of the universe.

iv) Rotating dyonic charged black holes in AdS(4) were constructed very recently and A microscopic explanation for their Bekenstein-Hawking entropy is still lacking. I plan to resolve this issue by applying the matrix model techniques, that I used in other similar contexts, on the holographic dual field theory.

３．研究の方法

In achieving my aims, holography and exact non-perturbative computations in QFTs are the main tools. In the following I will define some of the technical tools that I use to address the research objectives.

i) Topologically twisted index in three dimensions: it is defined as the path integral of gauge theories on a product of a Riemann surface of genus g -- with a partial topological twist to preserve some supersymmetry -- and a circle. The index can be reduced to a matrix model by employing the localization technique and is conjectured to reproduce the Bekenstein-Hawking entropy of dyonic supersymmetric AdS(4) black holes in its AdS/CFT guise.

ii) Black holes in four-dimensional N=2 gauged supergravity: consistent truncations of string and M-theory down to 4d gauged N=2 supergravity coupled to hypermultiplets is used to study supersymmetric AdS black objects in diverse dimensions. This approach had already been proven very useful in constructing new examples of AdS black objects.

iii) Gravitational blocks: recently, my collaborators and I discovered how to write down the entropy functional (whose Legendre transform gives the Bekenstein-Hawking entropy) of AdS black objects, with arbitrary rotation and generic electric and magnetic charges, in various dimensions. Knowing the entropy functional is of great importance in understanding the origin of black holes entropy since this object is indeed the logarithm of the partition function of the holographic dual field theory in the appropriate limits. This has been done by gluing gravitational blocks, which are basic building blocks that are directly inspired by the holomorphic blocks appearing in the factorization of supersymmetric partition functions.

４．研究成果

During the time of the research grant I managed to publish 5 papers in high-impact peer-reviewed journal, including Physical Review Letters. In addition, I have been invited to give seminars in different universities and institutes in Asia, Europe, and the US. This has given me the opportunity to expand the network of my collaborators, deepen my knowledge and strengthen my independence. All these wonderful experiences have uniquely shaped my character, strengthened my research confidence, and prepared me for the next stage of my career.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　5件）

１．著者名 Hosseini Seyed Morteza、Zaffaroni Alberto	４．巻 126
２．論文標題 Universal AdS Black Holes in Theories with 16 Supercharges and Their Microstates	５．発行年 2021年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.126.171604	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Hosseini Seyed Morteza、Hristov Kiril、Zaffaroni Alberto	４．巻 2021
２．論文標題 Rotating multi-charge spindles and their microstates	５．発行年 2021年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP07(2021)182	査読の有無 有
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１．著者名 Hosseini Seyed Morteza、Yaakov Itamar、Zaffaroni Alberto	４．巻 2022
２．論文標題 The joy of factorization at large N: five-dimensional indices and AdS black holes	５．発行年 2022年
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１．著者名 Hosseini Seyed Morteza、Hristov Kiril	４．巻 2021
２．論文標題 4d F(4) gauged supergravity and black holes of class F	５．発行年 2021年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 1~38
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP02(2021)177	査読の有無 有
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1．著者名 Hosseini Seyed Morteza、Hristov Kiril、Tachikawa Yuji、Zaffaroni Alberto	4．巻 2020
2．論文標題 Anomalies, black strings and the charged Cardy formula	5．発行年 2020年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 1~40
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP09(2020)167	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計9件（うち招待講演　9件／うち国際学会　8件）

1．発表者名 Seyed Morteza Hosseini
2．発表標題 Rotating multi-charge spindles and their microstates
3．学会等名 University of Tokyo (Hongo Campus)（招待講演）
4．発表年 2021年

1．発表者名 Seyed Morteza Hosseini
2．発表標題 A story of gravitational blocks and QFT indices
3．学会等名 Supersymmetric Black Holes, Holography and Microstate Counting（招待講演）（国際学会）
4．発表年 2020年

1．発表者名 Seyed Morteza Hosseini
2．発表標題 Anomalies, Black strings and the charged Cardy formula
3．学会等名 Mini-workshop: Recent Advances in QFT and Geometry, University of Oxford, United Kingdom（招待講演）（国際学会）
4．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Anomalies, Black strings and the charged Cardy formula
３．学会等名 Korea Institute for Advanced Study, Seoul, Korea（招待講演）（国際学会）
４．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Microstates of AdS black holes in string theory
３．学会等名 MIT Center for Theoretical Physics, Massachusetts, United States（招待講演）（国際学会）
４．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Anomalies, Black strings and the charged Cardy formula
３．学会等名 University of Amsterdam, Amsterdam, Netherland（招待講演）（国際学会）
４．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Anomalies, Black strings and the charged Cardy formula
３．学会等名 Instituto Superior Tecnico (IST), Lisbon, Portugal（招待講演）（国際学会）
４．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Holography of class F field theories
３．学会等名 Imperial College, London, United Kingdom（招待講演）（国際学会）
４．発表年 2020年

１．発表者名 Seyed Morteza Hosseini
２．発表標題 Anomalies, Black strings and the charged Cardy formula
３．学会等名 University of Padova, Padova, Italy（招待講演）（国際学会）
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

https://inspirehep.net/authors/1282083?ui-citation-summary=true

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
イタリア	University of Milano-Bicocca	INFN, sezione di Milano-Bicocca		
ブルガリア	Sofia University	Bulgarian Academy of Sciences		