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論文内容の要旨

M-theory is an eleven-dimensional theory, which has been proposed as a strong coupling limit of the type IIA superstring theory. It has been also expected that the M-theory includes the eleven-dimensional supergravity (11d SUGRA) as a low-energy limit. The 11d SUGRA consists of the graviton, gravitino and three-form gauge field. The three-form field in eleven dimensions electrically (magnetically) couples to two(five)-dimensional object. Such objects naturally appear as black brane solutions conserving a part of supersymmetries in the 11d SUGRA. On the analogy of the relation between such solutions in the ten-dimensional supergravities and objects in thesuperstring theories as string, NS5-brane and D-branes, we can expect that the M-theory has fundamental two- and five-dimensional objects. These objects are called as ``M2-brane`` and ``M5-brane``, respectively. In this thesis, we focus on Physics of the multiple M2-branes.

As well known, a low-energy limit of parallel N Dp-branes is described by the (p+1)-dimensionalU(N) maximally supersymmetric Yang-Mills theory. This U(N) gauge symmetry can be intuitively understood by the facts that open string includes spin-1 massless boson in its spectrum and have an U(1) charge called as a Chan-Paton factor. What is a low-energy effective theory of the parallel N M2-branes? Unfortunately, we have not an established answer to this question yet aswe will argue below.

From the single M2-brane analysis and implication of the AdS/CFT correspondence, we expect that the low energy effective theory for N M2-branes has the following properties: (1) Three dimensional conformal symmetry, (2) N=8 supersymmetry, (3) SO(8) R-symmetry, and so on. However, such a theory had not been found for long years. There are many reasons for this. One of most serious obstacle is difficulty of quantization of supermembrane. This prevents us from finding spectrum and something like a Chan-Paton factor for M2-branes. Another difficulty is that it is not easy to construct gauge theory with conformal and high supersymmetry except for four dimensions. Since Yang-Mills action is scale invariant only for four dimensions, we can use only Chern-Simons termof vector multiplet and marginal term of chiral multiplet for the construction. Indeed in 1990's, a maximal supersymmetric extension of Chern-Simons theory had been N=3.

In 2008, Aharony, Bergman, Jafferis and Maldacena (ABJM) has proposed a U(N)xU(N) theory with Chern-Simons levels k and -k coupled to bi-fundamental matters. Thistheory has N=8 supersymmetry for k=1,2 and N=6 supersymmetry for other values of k. It has been conjectured tobe dual to M-theory on $AdS_4 \times S^7/Z_k$ for $k<<N^{1/5}$, and to type IIA superstring on $AdS_4 \times CP^3$ in the planar large-N limit with the 't Hooft coupling constant $\lambda = N/k$ kept fixed.

From the viewpoint of quantum gravity, the ABJM theory is important since it may provide us with a nonperturbative definition of type IIA superstring theory or M-theory on AdS_4 backgrounds since the theory is well-defined for finite N. One may draw a precise analogy with the way maximally supersymmetric Yang-Mills theories may provide us with nonperturbative formulations of type IIA/IIB superstring theories on D-brane backgrounds through the gauge/gravity duality. In particular, the M-theory limit is important given that M-theory is not defined even perturbatively, although there isa well-known conjecture on its nonperturbative formulation in the infinite momentum frame in terms of matrix quantum mechanics. The planar limit, which corresponds to type IIA superstring theory, has interest on its own since it may allow us to perform more detailed tests of the gauge/gravity duality than in the case of AdS_5/CFT_4. In particular, we may hope to calculate the 1/N corrections to the planar limit, which enables us to test the gauge/gravity duality at the quantum string level, little of which is known so far.

In all these prospectives, one needs to study the ABJM theory in the strong coupling regime. As in the case of QCD, it would be nice if one could study the ABJM theo ry on a lattice by Monte Carlo methods. This seems quite difficult, though, for the fo llowing three reasons. Firstly, the construction of the Chern-Simons term on the lattice is not straightforward, although there is a proposal based on its connection to the pari ty anomaly. Secondly, the Chern-Simons term is purely imaginary in the Euclidean for mulation, which causes a technical problem known as the sign problem when one tries to apply the idea of importance sampling. Thirdly, the lattice discretization necessaril y breaks supersymmetry, and one needs to restore it in the continuum limit by fine-tu ning the coupling constants of the supersymmetry breaking relevant operators. This mi ght, however, be overcome by the use of a non-lattice regularization of the ABJM the ory based on the large-N reduction on S^3, which is shown to be useful in studying t he planar limit of the 4d N=4 super Yang-Mills theory.

In this thesis, Honda showed that the ABJM theory can be studied for arbitrary N at arbitrary coupling constant by applying a simple Monte Carlo method to the matrix model that can be derived from the theory by using the localization technique. This o pens upthe possibility of probing the quantum aspects of M-theory and testing the Ad S_4/CFT_3 duality at the quantum level. Here we calculate the free energy, and confir m the N^3/2 scaling in the M-theory limit predicted from the gravity side. He also fo und that the results nicely interpolate the analytical formulae proposed previously in t he M-theory and type IIA regimes. Furthermore, he showed that some results obtained by the Fermi gas approach can be clearly understood from the constant map contribut ion obtained by the genus expansion. The method can be easily generalized to the cal culations ofBPS operators and to other theories that reduce to matrix models. He also studys the super-symmetric Wilson loops in the ABJM theory. The result nicely interp olates the expressions at weak and strong coupling regions.

博士論文の審査結果の要旨

本多君は、超弦理論の分野において最近10数年の間のメインテーマの一つとなっている「AdS/CFT対応」を数値的に研究してきました。AdS/CFT対応とは、ゲージ理論と重力理論の間の双対性であり、1997年にマルダセナが提唱して以来、ブラックホール内部の理解や、インフレーションを含む初期宇宙論の研究に、大きな進展をもたらしました。博士論文では、超弦理論における双対性や、AdS/CFT対応に関連したレビューから始まり、本多君の数値的研究の成果が詳しく述べられ、100ページを超える大部となっています。また、本多君の論文は、２編が既にJournal of High Energy PhysicsとNuclear Physics Bに掲載されています。

AdS/CFT対応においては、超弦が膜状に凝縮した「ブレーン」という状態が重要な役割を果たします。特に、超弦理論のある種の極限で現れると考えられるＭ理論においては、Ｍ２ブレーンと呼ばれる状態が現れることが知られています。このＭ２ブレーンを記述する有効理論は、長い間明らかにされていませんでした。2008年になって、Ｍ２ブレーンの有効理論が超共形不変なゲージ理論の形で書けることがわかり、さかんに研究されてきました。本多君は、この超共形不変なゲージ理論に対して、モンテカルロ計算の方法を応用することにより、これまで解析が難しいとされていたパラメタ領域を数値的に調べることに成功しました。特に、Ｍ２ブレーンに関連して予測されていたAdS/CFT対応が第一原理から検証されたことは重要な成果と言えます。また、これまで解析的に調べられていたパラメタ領域の結果に対しても、見落とされていた項が存在することを明らかにしました。AdS/CFT対応という観点から、この項の物理的意義を明らかにするのは今後の課題と言えますが、本多君の得た結果は注目に値するものと考えられます。

モンテカルロ計算は、量子色力学の研究などにおいても大きな成功を収めておりますが、超共形不変なゲージ理論にそのまま適用する上では様々な困難が知られています。本多君は、ゲージ理論の持つ超対称性を利用して、理論に現れる力学的自由度を有限個に落とす「局所化」と呼ばれるテクニックをモンテカルロ計算と組み合わせることにより、この計算を可能にしました。この方法を他の理論に応用することにより、今後、超弦理論の様々な側面の研究が進展することが期待されます。

このように、本多君の博士論文は新しい手法に基づく、大変インパクトのある成果をわかりやすくまとめたものになっており、よって、論文審査において合格と判断しました。