氏　　　　名	松本耕一郎
学位（専攻分野）	博士（理学）
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論 文 審 査 委 員	主　　査　准教授　　西村　淳 教授　　小玉　英雄 准教授　　磯　暁 准教授　　筒井　泉 教授　　北澤　良久 准教授　　酒井　忠勝(茨城大学)

論文内容の要旨

In this doctoral thesis, we study the three-dimensional supersymmetric Yang-Mills theory from a viewpoint of matrix models. Particularly, we use the model which is called the IIB matrix model.

First of all, we give a brief review of the IIB matrix model which was proposed by Ishibashi, Kawai, Kitazawa and Tsuchiya in 1997. We can describe the following points as several properties of the IIB matrix model. This model can be regarded as a large N reduced model of the ten-dimensional N=1 supersymmetric $SU(N)$ Yang-Mills theory. It was shown that a large N gauge theory can be equivalently described by its reduced model on 0-dimensional spacetime. In this dimensional reduction, a spacetime translation is represented in the color of $SU(N)$ space, and the eigenvalues of bosonic matrices in the IIB matrix model are interpreted as the momenta of fields. Therefore, the basic assumption in this identification is that the eigenvalues are uniformly distributed. On the other hand, this model was proposed as the non-perturbative formulation of the type-IIB superstring theory. The following is several reasons that the IIB matrix model is a non-perturbative formulation of the type-IIB superstring theory. First, the action can be related to the Green-Schwarz action of a type-IIB superstring theory by taking a large N limit. In fact, we can describe an arbitrary number on interacting D-strings and anti-D-strings in the type-IIB superstring as diagonal blocks of bosonic matrices in the IIB matrix model. And the off-diagonal blocks of it represent interactions among these strings. The IIB matrix model describes not only the single-body system, but also the multi-body system of D-strings in the type-IIB superstring theory. Therefore, it must be clear that the IIB matrix model is not the first quantized theory, but a full second quantized theory of the type-IIB superstring. Then, we can point out a second evidence for the conjecture that the IIB matrix model is a non-perturbative formulation of the type-IIB superstring theory. The evidence is that Wilson loops of the IIB matrix model satisfy the string field equations of motion for the type-IIB superstring in the light-cone gauge. The IIB matrix model can describe joining and splitting interactions of fundamental strings created by the Wilson loops. Thus, the IIB matrix model could become a non-perturbative formulation of the type-IIB superstring theory. Finally, the dynamics of eigenvalues of bosonic matrices in the IIB matrix model represent the dynamical generation of spacetime in our universe. It can be interpreted that the spacetime consists of discretized points, and that eigenvalues of matrices represent their spacetime coordinates in the IIB matrix model. Thus, the dynamics of the IIB matrix model is such that the resulting eigenvalue distributions can be interpreted as any Riemannian geometry. For example, if the diagonal elements distribute within a manifold which extends in four dimensions but shrinks in six dimensions, then a natural interpretation is that the spacetime is four-dimensional.

The final property is a very characteristic and exciting topic in several properties of the IIB matrix model. There are considerable amount of investigations toward understanding the four-dimensional spacetime by using the IIB matrix model. For example, I may list the following studies: branched polymer picture, complex phase effects and mean-field approximations. These studies seem to suggest that the IIB matrix model predicts the four-dimensionality of spacetime. But it is difficult to analyze dynamics of the IIB matrix model in a generic spacetime. So it is considered that we would like to understand general mechanisms to single out the four-dimensionality of spacetime through the studies of concrete examples. In 2002, it was proved that fuzzy homogeneous spaces are constructed using the IIB matrix model. The homogeneous spaces are constructed as G/H where G is a Lie group and H is a closed subgroup of G. When a background field is given to bosonic matrices in the IIB matrix model, the stability of this matrix configurations can be examined by investigating the behavior of the effective action under the change of some parameters of the background. The stabilities of fuzzy S^2, fuzzy $S^2 \times S^2$, fuzzy $S^2 \times S^2 \times S^2$ and fuzzy CP^2 have been investigated in the past. By the above researches, we have found that the IIB matrix model favors the configurations of four-dimensionality and more symmetric manifolds.

Recently, there were interesting developments about constructions of curved spacetimes by matrix models. Hanada, Kawai and Kimura have introduced a new interpretation on the IIB matrix model in which covariant derivatives on any d-dimensional spacetimes can be described in terms of d large N bosonic matrices in the IIB matrix model. In this interpretation, the Einstein equation follows from the equation of the IIB matrix model, and symmetries under local Lorentz transformation and diffeomorphism are included in the unitary symmetry of the IIB matrix model. On the other hand, the relations between supersymmetric Yang-Mills theories on curved spacetimes and a matrix model have been proposed by Ishiki, Shimasaki, Takayama and Tsuchiya. The relations is as follows: the relation between the supersymmetric Yang-Mills theory on $R \times S^3$ and the supersymmetric Yang-Mills theory on $R \times S^2$, and the relation between the supersymmetric Yang-Mills theory on $R \times S^2$ and the plane-wave matrix model. They have made a connection between the supersymmetric Yang-Mills theory on $R \times S^3$ and the plane-wave matrix model up to showing the above relations. They also have showed that S^3 can be described in terms of three matrices which are configured by aligning representation matrices of $SU(2)$ on a diagonal.

We investigate the effective action of a deformed IIB matrix model with a Myers term on S^3 background describing by covariant derivatives on S^3 and irreducible representation matrices of $SU(2)$. In the both cases, we find that the highly divergent contributions at the tree and one-loop level are sensitive to the UV cutoff. However the two-loop level contributions are universal since they are only logarithmically divergent. We expect that the higher loop contributions are insensitive to the UV cutoff since three-dimensional gauge theory is super renormalizable. We can thus conclude that the effective action of the deformed IIB matrix model on S^3 is stable against the quantum corrections as it is dominated by the tree level contribution. Therefore, we find that the S^3 background is one of the non-trivial solutions of the IIB matrix model. We recall here that we have obtained the identical conclusions for the S^2 case. We thus believe that the two- and three-dimensional spheres are classical objects in the IIB matrix model since the tree level effective action dominates. We can in turn conclude that they are not the solutions of the IIB matrix model without a Myers term. We still expect that the IIB matrix model favors the configurations of four-dimensional spacetime.

論文の審査結果の要旨

松本耕一郎さんの学位論文は、Supersymmetric Gauge theories on Curved Spaces in IIB Matrix Modelと題し6章から構成されている。

第1章は、Introductionでゲージ理論と重力を統一する超弦理論を導入し、その非摂動論的定式化として行列模型を紹介している。

第2章は、Review of IIB matrix modelと題し、超弦理論の非摂動論的定式化として提唱されたIIB行列模型の対称性およびダイナミクスに関して論じている。

第3章は、Curved spaces in IIB matrix modelと題し、行列自由度で曲がった空間の共変微分を表現する花田、川合、木村等に依る一般論を紹介している。

第4章は、Super Yang-Mills theories in plane-wave matrix modelと題し、行列サイズ無限大極限において、無限個の2次元非可換球面上のゲージ理論が3次元球面上のゲージ理論と同等であることを、土屋等に倣って紹介している。この構成法は、平坦な時空において無限個のブレーンから高次元ブレーンを構成する処方箋の曲がった空間への拡張であり、3章の議論の具体的構成法とみなすことができる。

第5章は、Effective actions of IIB matrix model on S3と題し、3章4章で紹介された構成法による3次元球面上のゲージ理論の量子論的性質に関し、有効作用を2ループレベルまで計算することによって明らかにしている。3次元球面は、プリンシパルバンドルの一例であり、川合等の構成法が適用できる。実際3次元球面の共変微分は、SU(2)の生成子と同一視して構成される。行列模型の古典解としてSU(2)の生成子を得るようにすることにより、3次元球面上のゲージ理論を構成できる。3章と4章の構成法は、長波長領域は同一だが、短波長領域のスペクトルがことなっている。量子論的には、短波長領域から無限大の寄与がある場合が生じる可能性があるが、そのような事情が生ずると両者の構成法に差が生じうる。実際ツリーおよび1ループでは、有効作用は強く発散しており、両者は異なった有効作用を与える。2ループレベルでは、ログ発散に留まるため両者が同一の有効作用を与えることが見出された。3ループ以上では、理論の超繰り込み可能性のため有効作用は有限となり、両者は同一の寄与を与えることが予想される。

第6章は、Summaryと題し5章で示された行列模型によるS3上のゲージ理論の量子論的性質がまとめられている。物理的に興味深いS4ないしS3xR上のゲージ理論の非摂動論的な研究に対する拡張の可能性が指摘されている。

5章の内容は、金子・北澤・松本の共同論文としてPhys. Rev. Dに発表されており、松本さんは主要な計算および論文作成において中心的な役割を演じた。本論文は、オリジナルな研究成果およびその学問的背景を取りまとめた130ページに及ぶ力作であり、審査員一致して博士号(理学)授与に十分値すると判断した。