論文内容の要旨

論文題目　F-theory and its Applications to Phenomenology
(F 理論とその現象論的応用)

氏名　林　博貴

The Standard Model describes the physics around the Weak scale quite precisely. The flavor structure of Yukawa couplings is known to have very peculiar characteristics from experiments. In the Standard Model, Yukawa couplings are parameters and they are determined to fit the experimental results. Hence, the origin of the structure is difficult to be answered from the Standard Model itself. This issue essentially exists when we consider the Minimal Supersymmetric Standard Model (MSSM), which is a minimal supersymmetric extension of the Standard Model. Furthermore, the MSSM generically allows the presence of dimension-four proton decay operators whose appearance is so restricted from experiments that they are likely to be absent. A popular solution for it is to introduce a $\mathbb{Z}_2$ parity to the MSSM which prohibits the renormalizable proton decay operators. Again, it is hard to answer the origin of the symmetry from the MSSM itself. The MSSM indicates that the three gauge couplings will unify at such a high energy as $\sim 2 \times 10^{16}$ GeV. This phenomena implies the appearance of a Grand Unified Theory (GUT). Although the matter content of the Standard Model is classified in an elegant manner, the issues such as the flavor structure of Yukawa couplings and the presence of the dimension-four proton decay operators, still exist in GUT models also.

String theory, which is expected to be a fundamental theory including general relativity and quantum mechanics, could address those issues. One of the remarkable features of string theory is that it does not have an adjustable parameter in principle. An anomaly cancellation condition can determine a gauge group of a certain type of string theory and the gauge group includes typical gauge groups of GUT models. This characteristic opens the way to tackle the problems which would be hard to be solved purely from the viewpoint of four dimensional effective field theories. However, although string theory itself is unique, it has an enormous number of ground states. Since string theory is well defined in ten dimensions, we have to compactify the other six dimensions in order to realize four dimensional theories.

Then, we typically have a large number of the choices for the internal space. We cannot select a vacuum dynamically from the current understanding of string theory. The best we can do is that we first restrict the vacua from bottom-up conditions and study phenomenological results in the constrained region of the ground states.

One of the conditions can be the generation of all the Yukawa couplings in GUT models. For example, the Georgi – Glashow SU(5) GUT model has the up-type Yukawa coupling where gauge indices of the involved fields are contracted by using a rank five anti-symmetric tensor. This coupling is hard to be generated unless we consider Heterotic string theory with a gauge group of $E_8 \times E_8$ in five perturbative string theories. Nevertheless, there is another issue in Heterotic string theory. Since both gravity and gauge fields come from the quantization of closed strings, the Newton constant and the GUT gauge coupling obey special relations. In particular, when we consider the weak coupling region of Heterotic string theory, such relations typically do not match with the known experimental results.

There is, in fact, another way, so-called F-theory. F-theory can generate all the matters and Yukawa coupling in GUT models, and also can avoid the relations of the Newton constant and the GUT gauge group in Heterotic string theory. Therefore, F-theory describes a promising vacuum of string theory for GUT models. F-theory is a special compactification of type IIB string theory since it includes strong coupling effects of the string coupling as a configuration of an elliptic fibration over an internal geometry. This strong coupling property plays a crucial role in the generation of the up-type Yukawa coupling in the Georgi – Glashow SU(5) GUT model. Moreover, the geometry of F-theory naturally includes the backreaction of seven-branes. Fields in the representation of a GUT gauge group are localized on the seven-branes or along the intersection of the seven-branes. This localized property enables us to avoid the issue of the relation between the Newton constant and the GUT gauge coupling in Heterotic string theory.

To recap, we have the issues which would be difficult to be addressed from four dimensional Grand Unified Theories, and string theory could answer those questions. However, since string theory has a vast number of vacua, we restrict their region from bottom-up conditions. Then, F-theory describes an appropriate vacuum for GUT models. From this motivation, we study the phenomenological issues in GUT models constructed from F-theory compactifications in this thesis. In particular, we focus on the dimension-four proton decay problem in F-theory GUT models.

In this thesis, we first review F-theory and the proton decay problem in order to study the dimension-four proton decay problem in F-theory GUT models. We describe how F-theory seven-branes generate gauge symmetries. We explicitly see the generation of E-type gauge symmetries in F-theory compactifications. We, then, identifies matters in a certain representation of a gauge group with fields on seven-branes or localized on the intersections of seven-branes. The fields in the representation of a GUT gauge group can be captured by the 7+1 dimensional gauge theory on seven-branes. As for the proton decay, we review how the proton decay process is occurred in both non-supersymmetric and supersymmetric scenarios. In particular, we see that the presence of the renormalizable proton decay operators is highly restricted from experiments.

Next, we discuss the proposed solutions for the dimension-four proton decay operators in F-theory compactifications. There are four types of solutions in F-theory GUT models. They are, the $\mathbb{Z}_2$ symmetric scenario, the rank five GUT scenario, the factorized spectral surface scenario and the spontaneous R-parity violation scenario. Among them, the factorized spectral surface scenario is not without a theoretical concern. The scenario uses an U(1) symmetry which is supposed to be generated by taking a special configuration, a factorization condition, for the vacuum expectation value of adjoint Higgs fields on seven-branes in order to prohibit the dimension-four proton decay operators. However, the discussion is based on the 7+1 dimensional effective gauge theory on seven-branes and it only captures the physics near the seven-branes in the entire internal space. Hence, there remains a concern that this approximation nature might violates the severe restriction of the dimension-four proton decay operators. We call it Problem A. Moreover, there is indeed a region where the gauge theory description beaks down and it might be necessary to take into account this region to ensure the prohibition of the dimension-four proton decay operators. We call it Problem B. Given the severe constraint of the appearance of the dimension-four proton decay operators, the existence of the problem A and B in the 7+1 dimensional gauge theory description could be dangerous. Therefore, it is worth studying the prohibition of those operators without approximation, that is to say, from the consideration of the whole internal space. This analysis is the main part of this thesis and based on our original work.

The appearance of U(1) symmetries originate from the corresponding U(1) vector bosons. They are obtained from the expansion of three-forms in M-theory by a certain class of two-forms. Those two-forms can be understood as globally well-defined two-cycles over a complex two dimensional surface where seven-branes wrap through the Poincare duality. Globally well-defined means that they are not acted by monodromies when one circles around a locus in the surface. Hence, the generation of an U(1) symmetry can be studies by searching whether there is a monodromy invariant two-cycle over the surface. By setting the problem in this way, we do not rely on the 7+1 dimensional gauge theory description and can take into account the global effects from the consideration of the global geometry.

We take a special example of an $E_8 \to E_6$ symmetry breaking model in this thesis. Since this model contains both the problem A and problem B, it is enough to explore this model in order to find out whether the problem A and B affect the generation of the supposed U(1) symmetry. First we confine our attention to the 8D gauge theory region in order to justify our new method. The 8D gauge theory region corresponds to a restricted region in the internal space. By considering the monodromies associated with only the loops in the 8D gauge theory region, we find that an extra monodromy invariant two-cycles is indeed generated in the factorization limit. Hence, the new approach reproduced the result of the 7+1 dimensional gauge theory description. Then, we take into account the effects of the whole geometry and study whether there is a monodromy invariant two-cycle in the factorization limit. We show that there are two effects associated to the problem A and B and they indeed violate the generation of the supposed U(1) symmetry. We also find that the U(1) violating trilinear couplings are generated by the effects. Hence, the factorized spectral surface scenario actually fails to forbid the dimension-four proton decay operators. This means that the 7+1 dimensional gauge theory description is not enough to discuss the appearance of such an U(1) symmetry. We also list up loopholes for this scenario, but they requires another fine tunings.