論文の内容の要旨

Minkowski Flux Vacua on CM-type K3 × K3 Orbifolds
and their Particle Physics Implications

（CM型 K3 × K3 オービフォルド上のミンコフスキーフラックス真空解と
素粒子物理への示唆）

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The pursuit for an explicit model of quantum gravity theory of our Universe is one of the greatest problems in Physics. As string theory is strongly believed to be a consistent quantum gravity theory, it would be natural to ask if our Universe is realized as one of its solutions. String theory has 11- or 10-dimensional spacetime, so such solutions will have (1+3) non-compact spacetime dimensions which we see, and the rest of the dimensions extended to a compact space with small volume, and the structure along the compact dimensions will give us the degrees of freedom to play with. Such solutions must accommodate the great success of the Standard Model, or hopefully the Grand Unified Theories (GUTs) of particle physics, and the standard cosmology including the Big-Bang Nucleosynthesis (BBN), among many other things. We have already learned that a great extent of models of particle physics, including the GUTs, can be realized, especially in a framework of string theory called **F-theory**. Combining them with cosmology is, however, still challenging.

Of our particular interest is the combination of GUTs with a successful BBN. For the famous gauge coupling unification in the supersymmetric case to be achieved, it is necessary to keep the gravitino mass light, as there is an inevitable supersymmetry-breaking effect from the gravitino mass to the visible sector through the effect called anomaly mediation. For a successful BBN, on the other hand, there is a problem, called the moduli problem. Moduli, the scalar fields corresponding to the degrees of freedom of deforming the compact space, will have masses of at most the order of the gravitino mass if there is no mechanism giving masses in higher energy scale, typically spoiling the standard BBN scenario.

One can give masses of the order of the string scale to a certain kind of moduli in F-theory, called complex structure moduli, by turning on fluxes in the compact space. The mechanism, though, will also give large masses to gravitino. At the heart of the problem is that the fluxes are parametrized by *integers*. More explicitly, the fluxes are known to give the following superpotential W, to which the gravitino mass is proportional:

$$W \propto \int_Y G \wedge \Omega = \sum_i n^i \Pi_i. \tag{1}$$

Y denotes the compact space on which the F-theory is defined, G and Ω are differential forms that represent fluxes and the complex structure on Y, respectively, and n^i are integers corresponding to G, and Π_i are complex numbers corresponding to Ω. As one can see, it is hard to find a set of integers $\{n^i\}$ to achieve $W = 0$ for some set of complex numbers $\{\Pi_i\}$. It is even harder in general because the complex structure of Y, i.e. the value of Π_i, changes when the fluxes are changed. A generic flux vacuum, i.e. a generic 4-dimensional theory that arises from F-theory with non-trivial flux, will have gravitino mass of the order the string scale because the superpotential W is of the order the string scale.

In this thesis, we focus on a special kind of complex structure, called *CM-type*, and study if there are flux vacua with that complex structure to have $W = 0$ exactly, when no corrections to (1) is considered. In particular, we have studied flux vacua in F-theory on CM-type Calabi-Yau fourfolds of the form $\mathrm{K3} \times \mathrm{K3}/\mathbb{Z}_m$, where K3 denotes the K3 surface, the complex 2-dimensional and real 4-dimensional Calabi-Yau manifold, and "$/\mathbb{Z}_m$" means the identification of points in $\mathrm{K3} \times \mathrm{K3}$ by a $\mathbb{Z}_m$ action on both of the K3 surfaces, i.e. *orbifolding*. The case of $m = 2$ is intensively studied in Chapter 6, where we find explicit conditions supersymmetric $W = 0$ solutions, which can always be satisfied by any two identical copies of a CM-type K3 surface. We have found families of non-trivial flux vacua with $DW = W = 0$, i.e. vacua with massless gravitino, supersymmetry, and a vanishing cosmological constant, when no correction to the superpotential (1) or the Kähler potential is taken into account. Explicit conditions for supersymmetric $W = 0$ flux vacua in the case of $m > 2$ is found in Chapter 7.

The low-energy effective theory of such F-theory vacua with $m = 2$ is addressed in Chapter 8. We find that there are two types of geometries of the form $\mathrm{K3} \times \mathrm{K3}/\mathbb{Z}_2$, when applied to F-theory, and find a variety of gauge groups and (bi)fundamental matters charged under those groups in those vacua, but it seems to be unlikely that a GUT that explains our Universe is in this setup.

Finally, a more detailed summary of the results and possible future directions are found in Chapter 9.