Higgs mechanism and flavor structure from an extra dimension

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論 文 内 容 の 要 旨

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専　　攻　　物理学専攻

論文題目（外国語の場合は，その和訳を併記すること。）

Higgs mechanism and flavor structure from an extra dimension
(余剰次元から探るヒッグス・メカニズムとフレーバー構造)

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In this dissertation, we have studied the Higgs mechanism and flavor structure of the Standard Model from a viewpoint of higher dimensional gauge theories. Boundary conditions with respect to an extra dimension play crucial roles in our studies.

We introduce the thesis in Chapter 1. The Standard Model, which was first proposed in the 60's, is a four-dimensional gauge theory and has met great successes until today. The last missing piece of the Standard model, which is nothing but the Higgs particle, had been searched for by several high energy experiments, and finally in 2012 the discovery of a Higgs-like scalar particle was announced by the ATLAS and CMS experimental groups of the CERN Large Hadron Collider. With all the other results consistent with the Standard Model, we seem to have reached the end of a story. But we have not.

In spite of the great successes, the Standard Model still suffers from mysteries and problems. One of the mysteries is the origin of a negative mass square of the Higgs field. In the Standard Model, we need to prepare a negative mass square in order to obtain a nonvanishing vacuum expectation value of the Higgs field. The expecation value gives masses to the fermions through their Yukawa couplings. Even though a Higgs-like particle has been found, the origin of a negative mass square remains unknown. Another mystery is the origin of chiral fermions. In the Standard Model, the left- and right-handed chiral fermions belong to different representations of the gauge group. As a consequence, only the left-handed chiral fermions participate in the weak interaction. The origin of this chirality of the Standard Model should be understood but remains unknown. We also have the problem with fermion generations. In the Standard Model, we introduce three copies of fermions. Each copy possesses the exact same quantum numbers, and they mix among themselves through their Yukawa interactions with the Higgs field. The existence of the third generation was proposed to account for the violation of CP symmetry, and the existence of heavy fermions, unknown at that time of the proposal, was confirmed later in experiments. But it remains unknown why we have precisely three generations and not more. Furthermore, we have a problem with the masses of the fermions, so called the fermion mass hierarchy problem. In the Standard Model, the fermion masses are proportional to the Yukawa couplings. To describe the observed fermion masses, we have to give the Yukawa couplings a hierarchy spanning over five orders of magnitude. Why is there such a hierarchy? To answer the question, we must go beyond the Standard Model. Closely related to this hierarchy problem, the Standard Moldel itself has no mechanism to produce the right flavor mixing matrix. The strengths of generation-changing interactions are described by the Cabibbo- Kobayashi-Maskawa (CKM) matrix for the quarks and by the Pontecorvo- Maki- Nakagawa-Sakata (PMNS) matrix for the leptons. The elements of these matrices can be determined only experimentally. The Standard Model itself cannot provide a mechanism behind the mixing matrices. In addition to the mysteries and problems sketched above, the Standard Model suffers from many others. Thus, to resolve these, it is worth considering theories beyond the Standard Model.

Higher dimensional gauge theories are one of the candidates beyond the Standard Model. In higher dimensional gauge theories, we assume the existence of hidden extra spatial dimensions which play a crucial role to solve problems or clarify mysteries of the Standard Model. For example, there is a scenario in which we identify the Higgs particle as an extra component of a five-dimensional gauge field. In this scenario, the extra component of the gauge field takes responsibility for the Higgs mechanism. A feature of the scenario is the absence of a mass term (hence no negative mass square) for the Higgs field, since higher dimensional gauge invariance forbids the Higgs mass term. However, spontaneous gauge symmetry breaking can occur due to the geometry of extra dimensions. An orbifold compactification is another way to generate gauge symmetry breaking. An orbifold compactification can generate not only a gauge symmetry breaking but also a four-dimensional chiral fermion. This is how we may be able to solve mysteries and problems of the Standard Model using extra dimensions. We also have an attractive mechanism for the fermion mass hierarchy by localizing the Standard Model fermions at different points in one (more) extra dimension(s). The masses of four-dimensional fermions are determined by the overlap integrals of their wave functions, and hence are very sensitive to how the wave functions are localized. By coupling five-dimensional fermions to a scalar field with a kink background configuration, we can localize fermion's wave functions.

With these examples, we can now see how powerful higher dimensional gauge theories are to solve problems or clarify mysteries of the Standard Model. A higher dimensional gauge theory has an enough power to be the model beyond the Standard Model.

In higher dimensional gauge theories, we assume that extra dimensions are compactified not to contradict with experimental results. Boundary conditions imposed on higher dimensional gauge theories can affect dramatically the aspect of the Standard Model, which should be interpreted as the low energy effective theory.

The Standard Model particles are the zero modes of the Laplace operators with respect to extra dimensional coordinates, and the zero modes are sensitive to the adopted boundary conditions. A similar situation appears in a finite one-dimensional quantum mechanical system, e.g., the infinite square well potential. In the case of the infinite square well potential, we impose the Dirichlet boundary conditions for the wave functions. A constant profile cannot be a ground state solution in that case, and the ground state is given by a sine function. But if we impose instead the Neumann boundary conditions for the wave functions, the ground state is given by a constant profile. Now we can see that zero modes, or ground states, are really sensitive to the boundary conditions. Thus, the low energy effective theory of higher dimensional gauge theories, which is nothing but the Standard Model, is really sensitive to the boundary conditions of higher dimensional gauge theories.

There are several attempts classifying boundary conditions from a viewpoint of quantum mechanical supersymmetry. But there are no works which investigate general boundary conditions for higher dimensional fields as far as we know. The method we have adopted to derive general boundary conditions for higher dimensional fields can be found in the previous studies of one-dimensional quantum mechanics with point interactions. In these studies, possible point interactions in one-dimensional quantum mechanics have been classified according to the boundary conditions with the parameters of the U(2) group. Applying the same method to higher dimensional gauge theories, we derive general boundary conditions and investigate their effects on the low energy effective theory.

In chapter 2, we derive a general class of possible boundary conditions for a complex scalar field in the context of five-dimensional gauge theories defined on an interval. It is shown that general boundary conditions for the scalar field, that are compatible with several consistency requirements, are given by the Robin boundary condition. The Robin boundary condition is wider than the boundary condition commonly used and characterized by two parameters. With the Robin boundary condition the scalar field can acquire a nonvanishing vacuum expectation value even if the scalar mass square is positive. Usually a negative mass square is required to generate a nonvanishing vacuum expectation value. Furthermore, the vacuum expectation value of the scalar turns out to depend inevitably on the extra dimensional coordinate of the interval and be given in terms of the Jacobi elliptic functions. The phase diagram of broken/unbroken gauge symmetry possesses a rich structure in the parameter space consisting of the interval length, the scalar mass, and the boundary conditions.

In chapter 3, we have studied fermion's boundary conditions. It is shown that the most general boundary condition for a fermion is given by the Dirichlet boundary condition. Under the Dirichlet boundary condition, a four-dimensional chiral fermion zero mode may show up in the low energy effective theory. Moreover, we can introduce additional boundary points on the bulk without any inconsistency. The Dirichlet boundary condition for the fermion at additional boundary points does not contradict with the consistency requirements such as five-dimensional gauge invariance. In this situation, profiles of chiral fermion zero modes are split and localized, and we can realize three generations from a single five-dimensional fermion. An extra dimensional coordinate-dependent vacuum expectation value of a scalar, which may be produced by the Robin boundary condition, is useful for an explanation of the fermion mass hierarchy in this framework. As an application we construct a phenomenological model which can naturally explain the origins of fermion generations, quark mass hierarchy, and the Cabibbo- Kobayashi- Maskawa matrix from the geometry of an extra dimension.

In chapter 4, we discuss the vacuum expectation value of the Higgs doublet under a twisted boundary condition. Since our phenomenological model is constructed with a single generation of fermions, the model does not contain a CP phase degree of freedom. Under the twisted boundary condition, the vacuum expectation value of the Higgs doublet possesses a nontrivial extra dimensional coordinate-dependent phase. Through the overlap integrals, localized fermion zero modes pick up different phases to their masses that can be a source of a CP phase. Thus the phase of the Higgs vacuum expectation value can be a new source of the CP phase in the context of higher dimensional gauge theories. We apply this mechanism to our phenomenological model to fix the CP phase that appears in the Cabibbo- Kobayashi- Maskawa matrix.

（別紙１） 論文審査の結果の要旨

氏名	藤本 教寛		
論文題目	Higgs mechanism and flavor structure from an extra dimension （余剰次元から探るヒッグス・メカニズムとフレーバー構造）		
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要 旨

4次元時空間で定義された素粒子の標準模型は、現象論的には大きな成功をおさめている．最後の未発見粒子であったHiggs粒子が2012年に発見されて、模型の正しさは揺るぎないものとなった．しかし理論的には、標準模型は不完全で，クォーク・レプトンの質量行列は、理論のパラメターとして自由な値をとることができる．実験をフィットするようにパラメターの値を決めることしかできないのが現状である．

こうした標準模型の欠点を補う目的で研究の進められているのが、余剰次元の理論である．藤本は、直接の指導教員である坂本眞人とともに、5次元方向に有限の長さのある5次元時空間上の模型として、標準模型を拡張することによって、4次元標準模型の自由パラメターを理論的に決定する可能性を追求してきた．理論の整合性から5次元方向の境界条件に制約が出ることを解明し、許される境界条件の帰結を導出した．その結果、複素スカラー場が質量パラメターを作為的に選ばなくてもHiggs機構を起こすことを示し、さらに現実的なクォークの質量行列が、CP対称性を破る位相も含めて、5次元理論から自然に導かれることを示した．

論文の構成は以下のとおりである．第1章の序章では、上で説明した標準模型の欠点を説明し、標準模型を越えた理論の必要性を説いている．その一つの可能性として余剰次元への標準模型の拡張を位置づけている．さらに藤本の研究で重要となる場の満たす境界条件の役割を簡潔にまとめている．以後この論文では、有限な長さを持つ5次元方向への4次元ゲージ理論の拡張が議論されている．

第2章では、複素スカラー場が5次元方向の線分で満たすべき境界条件を解析している．ゲージ対称性によって許される最も一般的な境界条件がRobin境界条件（DirichletとNeumannの線形結合）であることを導き、さらにこの境界条件の下では、Higgs機構が、パラメターを作為的に選ばずとも、かなり自然に起こることを示している．

第3章では、フェルミ場の満たすべき境界条件を考察し、ゲージ対称性との整合性から、フェルミ場はDirichlet境界条件を満たさねばならないことを導いている．さらに線分上の複数の点においてDirichlet境界条件を課することにより、複数の世代のフェルミ粒子が得られることを示している．これにより1世代のフェルミ粒子しか含まない5次元の理論が、4次元では複数の世代のフェルミ粒子を表す可能性があることが分かる．この結果を使って、現象論的に正しい質量行列を再現する5次元理論を作っている．ただしCP対称性を破る位相を再現することはできていない．

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第4章では、標準模型におけるCPの破れを説明する可能性が、Higgs場の境界条件に「ひねり」をくわえることによって得られることを示している.この結果、標準模型を再現する5次元模型を構築することが可能であることがわかる.

第5章では、今後の展望が述べられている.特にレプトンの質量行列の導出と6次元以上の余剰次元理論の可能性が指摘されている.

余剰次元の理論にもいろいろあり、この論文で考察されている境界条件による物理の他にも、例えば5次元方向のゲージ場をHiggs場とみなすゲージHiggs理論など、いくつかの可能性が追求されている.藤本の研究業績は、余剰次元の研究が標準模型で解決できていない問題を解決する可能性を示唆している点で、非常に重要なものである.

本研究は、標準模型のHiggs機構とフレーバー構造について、その根源を余剰次元を持つ理論に求めたものであり、余剰次元の理論が標準模型の構造を説明する可能性について重要な知見を得たものとして、価値ある集積であると認める。よって、学位申請者の藤本教寛は、博士（理学）の学位を得る資格があると認める。