Doctoral Thesis

Theoretical studies on baryogenesis, neutrino mass, and dark matter in extended Higgs models

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Abstract

Although the standard model in particle physics is a successful theory, it does not include the origins of some observed phenomena, for example, the baryon asymmetry of the universe, neutrino oscillations, and the existence of dark matter. Therefore, it is inevitable that physics beyond the standard model exists. In the standard model, the Higgs sector is assumed to be the minimal one without any theoretical principle. Then, it would be natural to consider that a non-minimal Higgs sector is realized in the physics beyond the standard model.

Several models including extended Higgs sectors have been studied. In some of them, the extended Higgs sector provides the origin of the unexplained phenomena. For example, electroweak baryogenesis, a mechanism for the production of the baryon asymmetry, can occur in some extended Higgs sectors with CP violation. The neutrino mass, which causes neutrino oscillations, can be generated by the quantum effects of additional scalar bosons. Furthermore, if a new scalar boson is electrically neutral and stable, it is a candidate for dark matter.

Such models predict new particles whose mass scale is from the electroweak scale to the TeV scale. These are expected to be thoroughly tested in current and future experiments in the next few decades. Therefore, at the current stage of particle physics, it is a quite interesting and important study to examine the models with extended Higgs sector which includes the origins of the unexplained phenomena and to investigate how to test them by using various current and future experiments. In this doctoral thesis, I introduce two of our works based on this philosophy.

The first work is on electroweak baryogenesis in the two Higgs doublet model. In this model, the Higgs sector is extended by the second Higgs doublet. For successful electroweak baryogenesis, enough large CP violation and the strongly 1st order electroweak phase transition are essential, which are missing in the standard model. In the two Higgs doublet model, new CP-violating sources are supplied in the Higgs potential and the Yukawa interactions. In addition, the strongly 1st order phase transition can be realized by the non-decoupling effect of the additional scalar bosons.

Electroweak baryogenesis in the two Higgs doublet model has been investigated so far in some literature. However, it has been forced into a difficult situation as the experimental accuracy is improved. For example, the CP violation in the model is severely constrained by the measurements of the electric dipole moments. In addition, it has been revealed that the discovered Higgs boson behaves like the standard model one by the experimental result at the LHC so far.

In such a situation, a new scenario in the two Higgs doublet model was proposed. In this scenario, Yukawa interactions are assumed to be aligned in order to avoid dangerous flavor-changing neutral currents. To explain the observed nature of the Higgs boson, an alignment in the Higgs potential is also assumed so that coupling constants of the lightest Higgs boson coincide with those of the standard model Higgs boson at the tree level. Even under these simplifications, there are CP-violating phases in both the Higgs potential and the Yukawa interactions. By using the destructive interference between these CP-violating phases, it is possible to make the electric dipole moments small. Then,

the severe experimental constraint on the electric dipole moments can be avoided while keeping each CP-violating phase is large.

We investigate electroweak baryogenesis in this scenario. We find some benchmark scenarios where the observed baryon asymmetry can be reproduced under constraints from current experiments such as collider experiments, flavor experiments, and the measurements of the electric dipole moments. In these benchmark scenarios, the masses of the new scalar bosons are 300–400 GeV. They are expected to be directly produced in future high-energy colliders. In addition, in the benchmark scenarios, the prediction for the triple Higgs boson coupling is 35–55 % larger than the standard model prediction. This sizable deviation is expected to be detected in future Higgs precision measurements. We also discuss the verification of the scenarios by using other future experiments.

Next, we examine a TeV-scale extension of the two Higgs doublet model which can explain the origin of neutrino mass and the existence of dark matter in addition to the observed baryon asymmetry. In this model, a new Z_2 symmetry is imposed. The Higgs sector is further extended by new Z_2-odd particles: an isospin singlet charged scalar boson, a gauge singlet real scalar boson, and gauge singlet Majorana fermions.

New CP-violating sources are provided in the Higgs potential and the Yukawa interactions. The non-decoupling effect of the additional scalar bosons can make the electroweak phase transition strongly 1st order. Thus, baryon asymmetry can be produced by electroweak baryogenesis. Majorana-type masses of neutrinos are generated by the three-loop Feynman diagrams constituted by the additional scalar bosons and Majorana fermions. Furthermore, the real scalar boson or the lightest Majorana fermion is the candidate for dark matter.

As in the first work, we focus on the scenario, where the Higgs potential and the Yukawa interactions of the Higgs doublets are assumed to be aligned in order to explain the current experimental data. The severe constraints from the measurements of the electric dipole moments can be avoided by the destructive interference between the CP-violating phases in the Higgs potential and those in the Yukawa interactions.

We find a benchmark scenario in the model where all three phenomena can be simultaneously explained under the current experimental constraints such as collider experiments, flavor experiments, the measurements of the electric dipole moments, the direct search for dark matter, and the search for lepton flavor violation. The results of some numerical evaluations are shown. We also discuss the verification of the benchmark scenario by using various future experiments.