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Review

Rare lepton decays

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ABSTRACT

This article describes rare lepton decays, in particular, the rare processes in which lepton flavor of charged leptons is not conserved. Physics motivation, phenomenology, current experimental status and their future prospects for rare lepton decays are presented.

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1. Introduction

Our understanding of elementary particle physics is based on the Standard Model (SM). The SM has been a tremendous success to explain most of the physics phenomena so far. The SM has been scrutinized by numerous experimental tests, and it is still consistent with most precision measurements to date. Furthermore, it was a great success that the Brout–Englert–Higgs particle has been discovered at the Large Hadron Collider (LHC) at CERN at July 4th, 2012. The framework of the SM becomes almost complete.

On the other hand, it has been known that the SM is not considered to be a complete theory. From experimental sides, the SM cannot explain the dark matter, baryogenesis, inflation, the origin of neutrino masses, the flavor origin, and so on. From theoretical naturalness, the SM cannot explain the unification of the fundamental forces, the hierarchy problem, the cosmological constant, and the strong CP problem. It would require a large demand to obtain some hints of a more complete theory of particle physics. However, any new particles and new phenomena beyond the SM have yet to be observed at the LHC, at the time of year 2014. Therefore, more experimental searches for new physics other than the LHC are eagerly needed. Among many diversified opportunities, it has been known widely that search for rare lepton decays, in particular those with charged lepton flavor violation (CLFV), is one of the most promising research grounds to study new physics beyond the SM (BSM).

In Section 2, potential of new physics searches in rare processes in the framework of effective theories will be given. Physics motivation of new physics in rare lepton decays will be shown in Section 3. In Sections 4.1–4.3, we describe the phenomenology and experimental status of the most recent experiments which have searched for $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, and $\mu^- N \to e^- N$ conversion in a muonic atom, respectively. In Section 4.4, the searches for LFV in τ decays in low-energy e^+e^- colliders are briefly discussed, together with in-flight LFV processes to produce taus. In Section 5, future outlook is presented.

2. Flavor physics and new physics beyond the SM

One way to understand most particle physics phenomena is to use a simple effective theory which is composed of a gauge symmetry term and a gauge symmetry-breaking term, as follows:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{sym.break}}. \tag{1}$$

The first term is highly symmetric and can be predictable with high accuracy based on gauge symmetry, while the second term, which encodes the flavor structure of the SM, represents the connection to our natural world which is not fully symmetric. Flavor physics programs are aimed at understanding the second term. The evidence of the Brout–Englert–Higgs particle would suggest that the symmetry-breaking sector might have a minimal structure, and many of the particle physics problems could be included in the Higgs potential given by

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + Y^{ij}\Psi_L^i\Psi_R^j\Phi + \frac{g_{ij}}{\Lambda}\Psi_L^i\Psi_L^{jT}\Phi\Phi^T, \tag{2}$$

where Φ and Ψ are the Brout–Englert–Higgs particle and the fermions, respectively, and Y^{ij} is the Yukawa coupling. The last term represents the effective dimension-five neutrino mass term and Λ is its new physics scale. These third and fourth terms are responsible for masses and flavor mixing of both quarks and leptons.

The two key open questions concerning the "origin of flavor" in flavor physics are (1) *what determines the observed pattern of masses and mixing angles of quarks and leptons?* and (2) *which sources of flavor symmetry breaking are accessible at low energies?* Owing to the lack of theoretical guidance, even with the precise measurements of the quark mixing parameters, it is difficult to address the first question so far. The second question is being studied by a series of high-precision measurements of flavor-changing processes. And it is believed that a study of favor symmetry breaking would suggest a hint of new physics, since it cannot be explained by the SM itself.

We indeed do expect small but detectable deviations from the SM predictions in selected special flavor-changing processes. They are the flavor-changing processes with suppressed SM contributions, or the SM-forbidden processes with no SM contribution. The former corresponds to the case in the quark sector, whereas the latter does to the case in the lepton sector. They are shown in the following.

Quark sector: In the quark sector, almost all measurements show overall agreement with the Cabibbo–Kobayashi–Maskawa (CKM) picture; a remarkable success of the model. On the other hand, this success may be embarrassing since it could exclude possible large contributions of the BSM at the TeV scale. For instance, new physics may be included as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2}O_{ij}^{(6)}, \tag{3}$$

where the second term represents the new physics contribution and C_{NP} and Λ are the coupling constant and the energy scale of the BSM respectively, and $O_{ij}^{(6)}$ is a dimension-six operator. For example, from the measurements of Δm_K, Δm_D, Δm_{B_d}, Δm_{B_s}, CP violating parameters for K, D, B_d and B_s, the energy scale of BSM $\Lambda \sim \mathcal{O}(10^3)$ TeV in the case of $C_{\text{NP}} = 1$ is assumed, or C_{NP} is very small, of the order of $\mathcal{O}(10^{-5})$ to $\mathcal{O}(10^{-11})$ if $\Lambda = 1$ TeV is assumed (see Table 1).