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Viability of minimal left–right models with discrete symmetries

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Abstract

We provide a systematic study of minimal left–right models that are invariant under P, C, and/or CP transformations. Due to the high amount of symmetry such models are quite predictive in the amount and pattern of CP violation they can produce or accommodate at lower energies. Using current experimental constraints some of the models can already be excluded. For this purpose we provide an overview of the experimental constraints on the different left–right symmetric models, considering bounds from colliders, meson-mixing and low-energy observables, such as beta decay and electric dipole moments. The features of the various Yukawa and Higgs sectors are discussed in detail. In particular, we give the Higgs potentials for each case, discuss the possible vacua and investigate the amount of fine-tuning present in these potentials. It turns out that all left–right models with P, C, and/or CP symmetry have a high degree of fine-tuning, unless supplemented with mechanisms to suppress certain parameters. The models that are symmetric under both P and C are not in accordance with present observations, whereas the models with either P, C, or CP symmetry cannot be excluded by data yet. To further constrain and discriminate between the models measurements of B-meson observables at LHCb and B-factories will be especially important, while measurements of the EDMs of light nuclei in particular could provide complementary tests of the LRMs.

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1. Introduction

Left–right models (LRMs) have been studied extensively as possible physics beyond the SM (BSM) [1–5]. LRMs extend the standard model (SM) gauge-group to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and possess several attractive features. They offer an interpretation of the $U(1)$ generator in terms of baryon and lepton number and naturally allow for neutrino masses through the see-saw mechanism. Furthermore, the gauge group of the LRM can appear in grand unified theories (GUTs), such as $SO(10)$ and E_6, as an intermediate step [6], while avoiding the $SU(5)$ group which has problems with proton decay. But perhaps their most appealing feature is the possibility of having a symmetry between left- and right-handed particles at high energies, a so-called LR symmetry. LR models employing such a symmetry, LR symmetric models (LRSMs), restore parity (P) and/or charge conjugation (C) invariance at high energies, thereby explaining the P- and/or C-violating nature of the SM as a low-energy effect.

From a theoretical standpoint, the most attractive LRSMs might be those which exhibit both P and C symmetries, and thereby CP symmetry, at high energies. Such models *in principle* can explain the observed CP violation as resulting from spontaneous CP violation rather than from explicit CP violation as in the SM. However, the LR symmetries of such "$C+P$" models strongly constrain the left and right CKM matrices, dictating the amount and pattern of CP and flavor violation. For the so-called minimal LRSMs, which are most commonly considered and which have a minimally extended Higgs sector, these model constraints turn out to be incompatible with measurements of Kaon and B-meson mixing, as will be discussed. Therefore, minimal LRSMs require explicit P or C violation. It is the goal of this paper to assess the viability of these options, of which many aspects have already been discussed in the literature before. Nevertheless, it seems useful to collect the available results, combine and supplement them, and arrive at clear conclusions about which models are ruled out by current experimental constraints and which models require an unacceptably large amount of fine-tuning. Apart from the LRSMs with "$C + P$", P or C symmetry, we also will consider an LRM that is CP symmetric, but not necessarily P and C symmetric. Since this option does not correspond to an LR symmetry, it is not a left–right *symmetric* model.

For all these models we consider the quark and Higgs sectors, review the relations between the left- and right-handed CKM matrices, consider the possible vacua and calculate a measure of the fine-tuning in the Higgs potential in each case. Furthermore, we give an overview of the relevant experimental constraints on the different LRMs, considering bounds from direct searches at the LHC, from B-meson-mixing measurements at LHCb and B-factories, from Kaon mixing, and low-energy observables, such as beta decay and electric dipole moments (EDMs). As said, in the "$C + P$" models current constraints are sufficiently strong to exclude them, but for the other options future measurements, in particular on CP violation by LHCb will be able to limit the options further considerably and may also be able to differentiate between the C-symmetric and P-symmetric LRMs. Measurements on EDMs for the neutron, but also for the proton, other light nuclei and the electron would offer additional tests of LRMs. Currently the LR scale as given by the mass of the right-handed W boson, commonly referred to as W' boson, is required to be at least 2 TeV by direct searches and in the case of P or C-symmetric LRSMs 3 TeV by indirect Kaon and B-meson constraints [7]. In the coming decade this bound could extend to 8 TeV or higher. As this scale gets pushed upwards, the already considerable if not huge fine-tuning required in the models will increase further and the models become increasingly less likely scenarios. These bounds and perhaps the fine-tuning may be weakened though by considering non-minimal [8,9] and/or less symmetric models [10–12]. We will not