Annals of Physics 364 (2016) 53–67

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

A model with two inert scalar doublets

A.C.B. Machado *, V. Pleitez

Instituto de Física Teórica–Universidade Estadual Paulista, R. Dr. Bento Teobaldo Ferraz 271, Barra Funda, São Paulo - SP, 01140-070, Brazil

ARTICLE INFO

Article history:
Received 16 June 2015
Accepted 23 October 2015
Available online 31 October 2015

Keywords:
Inert-doublets model
Dark-matter

ABSTRACT

We consider an extension of the standard model (SM) with three $SU(2)$ scalar doublets and discrete $S_3 \otimes \mathbb{Z}_2$ symmetries. The irreducible representation of S_3 has a singlet and a doublet, and here we show that the singlet corresponds to the SM-like Higgs and the two additional $SU(2)$ doublets forming a S_3 doublet are inert. In general, in a three scalar doublet model, with or without S_3 symmetry, the diagonalization of the mass matrices implies arbitrary unitary matrices. However, we show that in our model these matrices are of the tri-bimaximal type. We also analyzed the scalar mass spectra and the conditions for the scalar potential is bounded from below at the tree level. We also discuss some phenomenological consequences of the model.

1. Introduction

In 2012 it was discovery at the LHC a neutral spin-0 resonance with properties (mass and couplings) that are compatible, within the experimental error, with those of the scalar SM-Higgs boson [1,2]. However, on the one hand, there is no experimental evidence confirming that only one of such sort of scalars does exist. On the other hand, there are experimental evidence, e.g. the existence of Dark Matter (DM) and neutrinos masses and mixing, that strongly suggest that the SM is not the ultimate theory of nature. In this context, we may need to add new scalars, to play the role of the DM candidate or in order to justify the difference between the mass scale of the neutrinos and the charged leptons. The question is, if there are more scalar doublets, how many of them? The simplest case is to add one more doublet. This is well motivated because it allows spontaneous *CP* violation if at the same time

* Corresponding author.
E-mail addresses: ana@ift.unesp.br (A.C.B. Machado), vicente@ift.unesp.br (V. Pleitez).

http://dx.doi.org/10.1016/j.aop.2015.10.017

flavor changing neutral currents (FCNC) are allowed [3,4]. The latter processes strongly constrain the masses and the mixing angles in the scalar sectors. For a recent review of the phenomenology of the two Higgs doublet models (2HDM) see Ref. [5]. The next simple situation is having three doublets in which it is possible to have spontaneous and hard *CP* violation [6] and at the same time to avoid FCNC if some extra symmetries are introduced. Next, we can introduce more Higgs scalar doublets, for instance, it may be motivated by the implementation of the Peccei–Quinn symmetry and the unification of the three interactions, see Ref. [7] and references therein.

Among all these possibilities the case of three doublets with the same quantum number is interesting if we assume that the replica of three generations occurs not only in the fermion sector but also in the scalar sector. However, a general three doublet model (3HDM) has a very complicated scalar potential with six parameters with dimension of mass (μ^2s), and many dimensionless ones (λs). Notwithstanding in physics, when the degrees of freedom augment it motivates the introduction of new symmetries. In fact, to reduce the number of parameters in the scalar sector usually symmetries, like $\mathbb{Z}_2$ [8], are introduced. In some cases one of the scalar doublets is inert. However, the Z_2 symmetry still allows four μ^2s and 23 dimensionless real parameters. The possibility of an S_3 symmetry is also explored in [9,10]. In the case of the 3HDM with S_3 symmetry has only two parameters with dimension of mass and eight dimensionless ones i.e., in terms of the number of parameters the scalar potential in the 3HDM plus a S_3 symmetry has almost the same as the general 2HDM. The problem with this model is that in general several possibilities are allowed, and some of them are not physical because they imply the existence of massless physical neutral scalar. Another difficulty is the existence of FCNC effects [11]. Usually also the neutral scalar with mass of 125 GeV is obtained only in the decoupling limit [10]. All these effects arise mainly because, (i) the mass matrices mix all the scalars in each charge sector and, because of this, the unitary matrices that diagonalize the respective mass matrices are general ones in each case; (ii) an arbitrary vacuum alignment is assumed with all the vacuum expectation values (VEVS) being different.

Here we will consider a 3HDM with an S_3 symmetry in which the SM-like scalar is automatically identified without requiring a decoupling limit. This is a consequence of a particular vacuum alignment and the absence of FCNC at tree level is a consequence of this vacuum alignment plus the condition of fermions transforming trivially under the symmetry S_3. Another important consequence of this vacuum alignment is that the scalars in the S_3 doublet are inert [12,13]. It means that they do not contribute to the spontaneous symmetry breaking and do not couple to fermions. They interact only with the vector and the other scalar bosons.

The SM extensions with one inert doublet model (IDM) as a candidate to dark matter have been already considered in Refs. [14–22]. However having two inert doublets allows to have a multi-component dark matter scenario [23–25], because not only the real scalar and pseudoscalar may be DM as in the IDM, but now we have two real scalar fields and two pseudoscalar ones, each of them may contribute to the DM density.

The outline of this paper is as follows. In Section 2 we give the most general scalar potential involving three Higgs doublets which is invariant under the gauge and S_3 symmetries. We also consider in that section the mass spectra in the scalar sector when all VEVs satisfy the alignment $v_1 = v_2 = v_3 = v = v_{SM}/\sqrt{3}$ and the singlet (S) and the doublet (D) of S_3 are originated from a triplet i.e., in the reducible representation. In this situation there are mass degenerate states in each scalar sector because a residual S_2 symmetry remains. However the mass degeneracy may be lifted by introducing terms that break the S_2 symmetry softly. We dubbed this case A. In Section 4 we consider the case when $S = H_1$ and $D = (H_2, H_3)$ with $v_1 = v_{SM}$ and $v_2 = v_3 = 0$. We call this case B. We show that both cases, *before* the spontaneous symmetry breaking (SSB), are related by a weak basis transformation. However, *after* the SSB both cases are still equivalent but only the vacuum alignment is considered here. We also consider in this case the situation when the S_2 symmetry is softly broken avoiding the mass degeneracy, in this case the equivalence between both cases is also lost. The Yukawa interactions are the same in both cases and are briefly discussed in Section 5. In Section 6 we study the positivity of the scalar potential at the tree level, while in Section 7 we consider some phenomenological consequences. Our conclusions are in Section 8 and in the appendices we show the constraint equations for arbitrary VEVs, for case A in Appendix A, and for case B in Appendix B.