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PRODUCTION BEHAVIOUR OF THE 5-PLET HIGGS BOSONS OF THE HIGGS TRIPLET MODEL IN Z^0 – DECAY

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This paper envisages the nature of production of the 5-plet Higgs bosons of the Higgs triplet model (with $\varrho = 1$) of electroweak interactions in Z^0-decays assuming the masses of these Higgs bosons to be such that their production are kinematically admissible in these decays. It has been pointed out that in these decays production modes involving a single Higgs boson may occur uninhibited, whereas the ones composed of two Higgs bosons must exhibit model-independent suppressions. Accordingly, the former modes will be more suitable than the latter ones for unveiling the signatures of the Higgs bosons as highlighted in this paper.

1. Introduction

The standard model [1] (SM) described by the group $SU(2)_L \times U(1)_Y$ is the gauge field theory of electroweak interactions. The minimal version of this model exploits one complex Higgs doublet. After spontaneous breaking of the $SU(2)_L \times$ $\times U(1)_Y$ symmetry to $U(1)_{em}$ symmetry, the Higgs sector of this model contains only one physical Higgs boson which is electrically neutral and, needless to mention, a fundamental scalar. This boson, as is well known, remains to date an experimentally elusive object. This in turn points the fact that the Higgs sector of the minimal SM is yet to receive experimental justification. One important remark is in order here. The minimal SM is rather rich in its particle content in sharp contrast to its Higgs sector. The important point to be recognized in this context is that there are no compelling theoretical and experimental reasons to believe that the SM should have only one complex Higgs doublet at its disposal as in the case of its minimal version. In fact, nothing prevents the SM from having an extended Higgs sector [2-4] which may include the Higgs scalars belonging to representations of SU(2) other than doublets. The gains of such an extended Higgs sector are that it does not have to depend on any idea (such as supersymmetry) which is foreign to the SM, and also it does not necessitate any extension of the gauge group. An extended Higgs sector of the type mentioned above implies that triplets of Higgs scalars may be incorporated within the framework of a nonminimal version of the SM. Such a version of the SM is generally referred to as a Higgs triplet model.

In this paper we shall be concerned with that version of Higgs triplet model (HTM) which was proposed by Georgi and his co-workers [2]. This model embodies [2-5], in addition to the usual complex SU(2) doublet Φ of Higgs fields (with hypercharge $Y = 1$), one real triplet ξ of Higgs fields with $Y = 0$ and one complex triplet χ of Higgs fields with $Y = 2$. The doublet and triplet Higgs fields are expressed as [3-5]

$$\Phi = \begin{bmatrix} \phi^+ & \phi^{0*} \\ \phi^0 & \phi^- \end{bmatrix}, \qquad \psi = \begin{bmatrix} \chi^{++} & \xi^+ & \chi^{0*} \\ \chi^+ & \xi^0 & \chi^- \\ \chi^0 & \xi^- & \chi^{--} \end{bmatrix}.$$

The Higgs potential is constructed by requiring that it possesses a global SU(2) symmetry, namely, the "Custodial SU(2) symmetry". This symmetry is broken in such a way that it remains intact for the neutral fields. This is achieved by imparting the vacuum expectation values (VEV) to the neutral fields as shown below [2-5]

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & a \\ a & 0 \end{bmatrix}, \qquad \langle\psi\rangle = \begin{bmatrix} 0 & 0 & b \\ 0 & b & 0 \\ b & 0 & 0 \end{bmatrix}$$

which clearly reveal that the custodial symmetry among the neutral Higgs fields is a diagonal SU(2). The VEVs a and b are related to the masses of the weak vector bosons through the following relation

$$M_W^2 = M_{Z^0}^2 \cos^2\Theta_W = \frac{g^2}{4}\left(a^2 + 8b^2\right).$$

In this model the tree-level unitarity condition, i.e., $\varrho = 1$ with $\varrho = M_W^2/M_{Z^0}^2 \cos^2\Theta_W$ is satisfied, despite the fact that the Higgs doublet as well as Higgs triplets can contribute to the masses of the W and Z^0 bosons by virtue of the custodial symmetry of the neutral Higgs fields. After the absorption of the Goldstone fields (which impart masses to the W and Z^0 bosons), the remaining ten physical Higgs bosons are classified according to their transformation behaviour under the custodial SU(2). These physical scalars are grouped into a 5-plet composed of $H_5^{++,+,0,-,--}$, a 3-plet consisting of $H_3^{+,0,-}$ and two singlets H_1^0, H'^0_1; H_3^0

is a pseudo-scalar. We may also note that the new physics of the above mentioned Higgs bosons is indeed spectacular [3-5].

Needless to emphasize that the experimental observation of at least some of the Higgs bosons referred to above is crucially important for the empirical justification of the HTM. For this purpose, the 5-plet Higgs bosons $H_5^{++,+,0,-,--}$ are considered to be that best candidates. This point is reflected in the fact that the HTM admits their couplings [3-5] to the vector bosons of the types Vector-Vector-Higgs as well as Higgs-Higgs-Vector. Therefore, the 5-plet Higgs bosons are expected to be produced via the following tree-level decays:

$$Z^0 \to H_5^+ \underbrace{W^{-*}}_{\hookrightarrow l^-\overline{\nu}_l} \quad , \quad Z^0 \to H_5^- \underbrace{W^{+*}}_{\hookrightarrow l^+\nu_l} \quad , \quad Z^0 \to H_5^0 \underbrace{Z^{0*}}_{\hookrightarrow l\bar{l},\, \nu_l\overline{\nu}_l} \tag{A}$$

which give rise to the single Higgs boson production (l denotes a lepton) and,

$$Z^0 \to H_5^{++} H_5^{--}, H_5^+ H_5^- \tag{B}$$

which lead to pair production of charged Higgs bosons. It is worthwile noting the important point that H_5^{++} and its charge conjugate cannot be produced singly in Z^0-decays because of the charge conservation principle. In what follows we shall assume that the decays (A) and (B) are kinematically feasible as is the case for low-mass 5-plet Higgs bosons ($m_H < m_{Z^0}/2$).

In order to prepare the necessary background for our motivation of investigating this problem we note that the production of the Higgs bosons via the decays (A) and (B) may take place uninhibited according to the HTM as there are no provisions for suppressions of these decays within the framework of the model. This is because, as noted above, these decays can occur at the tree-level [3-5] in the scenario of the model. This fact, however, does not rule out the possibility of occurrence of *model-independent* suppressions of these decays.

In our recent papers [6,8,9] we have argued that some of the tree-level decays predicted by the minimal SU(5) GUT, SUSY/SUGRA GUT, and minimal SUSY-$SU(2)_L \times U(1)_Y$ must exhibit model-independent suppressions caused by the dimensionality-based decay selection rule, namely the pseudo-dimension rule [6-12]. This rule has been exploited in the present paper to study the nature of production of the Higgs bosons taking part in the decays (A) and (B) referred to above. It will be evident from the discussion that follows the decays (A) are favoured by this rule which, however, forbids (and as such suppresses) the decays (B). Consequently, the production modes involving a single Higgs boson may take place without any inhibition whereas the ones composed of two Higgs bosons must suffer suppression. As an outcome of this, the former modes will serve as a much more convenient platform than the latter ones for experimenatal searches of evidence of the Higgs bosons which are produced via the decays (A) and (B).

2. *The pseudo-dimensional rule*

We now proceed to discuss briefly the pseudo-dimension rule [6-12] to be abbreviated hereafter as the PD rule. For the reason to be clear afterwards, this rule covers all types of decays, i.e., strong, electromagnetic, weak and superweak decays. As this rule is based on the pseudo-dimensions of the fields of the particles involved in a decay process, we first focus our attention on these dimensions. In this paper, however, we shall be concerned with pseudo-dimensions of *free* fields. This is because for such fields pseudo-dimensions are well defined quantities. These dimensions are defined by requiring that they coincide with the canonical dimensions at least for the following three categories of fields:

(i) all spin-half fields carrying *integral* scalar quantum numbers;

(ii) all spin-zero fields having *integral* scalar quantum numbers;

and

(iii) all spin-one massless fields.

As is well known, the numerical value of the canonical dimension of all fermion fields is $\frac{3}{2}$ and that of all boson fields (including a photon field in its 4-vector description) is equal to 1.

In what follows we shall denote by d the numerical value of the pseudo-dimension of a (free) field carrying spin J. By making use of the requirements on d mentioned above, one can obtain the following relations [6,8]:

$$d = 3J \text{ for a field having } J{\neq}0 \tag{1}$$

which is valid for all fermion fields except quark fields and all boson fields with $J{\neq}0$ except massless vector fields;

$$d = 1 \text{ for a field having } J = 0 \tag{2}$$

irrespective of its scalar quantum numbers;

$$d = 1 \quad \begin{array}{l}\text{for a massless vector field}\\ \text{(like a photon or gluon field);}\end{array} \tag{3}$$

and

$$d = \frac{1}{2} \quad \begin{array}{l}\text{for a spin-half field with}\\ \text{fractional scalar quantum numbers}\\ \text{(like a quark field).}\end{array} \tag{4}$$

It is worth stressing that the pseudo-dimensions of the fields in general cannot be obtained from a fundamental Lagrangian, as their values are different from the respective values of canonical dimensions, except for the three categories of fields mentioned above. The situation is very similar to the case of "anomalous dimensions" [13-17] which are also not derivabile from a Lagrangian. This fact, however, does not underestimate the tremendous importance of the anomalous dimensions. This point becomes immediately transparent if we recall their bearing on particle decays [3,17] as well as deep inelastic scattering [14-16]. A look into our earlier papers [6-12] reveals the impressive role played by the PD rule which banks on pseudo-dimensions of fields. Finally, we turn our attention on the status of these dimensions. This point turns out to be important because of Mandelbrot's observation [18] that pseudo-dimensions exhibit dimension-like behaviour but are not dimensions in the strict sense of the term. It may be recalled, this observation has been made in the context of the Hausdorff-Besicovitch dimensions [18] and as such is not generally valid for the pseudo-dimensions of *fields*. This is because the latter dimensions reduce to canonical dimensions (which are, needless to mention, actual dimensions of free fields) for some special categories of fields. This in turn implies that the pseudo-dimensions of *fields* take the interpretation of some kind of dimensions in general and turn out to be actual dimensions in particular for the three categories of fields referred to above.

We now define the quantities in terms of which the PD rule is stated and also point out the assumptions for framing this rule. We will denote by d_u the pseudo-dimension of the field of a particle A undergoing the decays $A \to BC$, EFG, ... Further, we will denote by D the sum of the pseudo-dimensions of the fields of the particles constituting a decay mode of A. Therefore by definition $D = d_B + d_C$ for the two-body mode BC, $D = d_E + d_F + d_G$ for the three-body mode EFG and so on. In this context, it is worth mentioning that dimensions are well defined quantities for free fields only and they turn out be "anomalous" [13-16] for interacting ones. Obviously, the d_u and D are well defined for free fields. Accordingly, in order to treat these quantities as well defined ones, we shall ignore the "short-distance effects" [13-16] as well as possible final state interactions.

The PD rule is stated in terms of d_u and D defined above. This rule reads [6-12]: the allowed decays of a particle are governed by *one and only one* of the two constraints

$$d_u \geq D \tag{5a}$$

and,

$$d_u \leq D \tag{5b}$$

where d_u is fixed for a given decaying particle whereas D can take in general a finite spectrum of discrete values corresponding to the finite number of the decay modes of the particle concerned. We have already underlined the fact that the PD rule covers strong, electromagnetic and weak (including superweak) decays. This point is manifested in the statement of this rule which does not refer to the nature of interactions responsible for the decays of a particle. It is worth stressing here the fact that the dimension of a field turns out to be its intrinsic property as a field cannot be a dimensionless entity, be it a free field or undergoing any type of interaction, under all possible circumstances. From this it follows that a dimensionality-based decay selection rule, such as the PD rule, must be of general validity. However, as emphasized earlier, dimensions are affected by interactions. In passing we note that the PD rule is an ordinary (i.e., approximate) decay selection rule because of the assumptions (stated above) underlying it.

We now outline the procedure for the application of the PD rule to the decays of a given particle. Our first step to accomplish this objective, as implied by the statement of this rule, is to specify the constraint operative in the decays of the particle concerned. This is because the PD rule of itself does not specify which one of the two constraints, given by relations (5a) and (5b), holds true for the decaying particle under considerations. This fact, however, does not pose any problem as specification of the constraint appropriate for a given decaying particle can be made by any one of the following two methods which suits our purpose: (i) direct method and (ii) indirect method.

The direct method is applicable to a particle for which the *most* dominant decay has an appreciable branching ratio. It makes use of the dominant decay (satisfying the requirement just mentioned) of the particle concerned as such a decay must necessarily enjoy the status of a PD rule – allowed decay in order that this rule can have any claim to be a reliable decay selection rule. To illustrate the direct method, we consider $\varrho(774)$-decay for which the most dominant mode is $\varrho \to 2\pi$ having a very appreciable branching ratio. For the decaying field ϱ, we have $d_u = 3$ which follows from Eq. (1), and for 2π mode, $D = d_\pi + d_\pi = 1 + 1 = 2$ since $d_\pi = 1$ as evident from Eq. (2). Clearly, the most dominant decay $\varrho(d_u = 3) \to 2\pi$ $(D = 2)$ indicates that the constraint operative in ϱ-decay must be $d_u \geq D$. It is worth mentioning here that the task of specification of the constraint for a decaying particle really amounts to fixation of the sign of the inequality appearing in the relevant constraint as the equality sign occurs in both the constraints given by relations (5a) and (5b). We also note that the direct method runs into difficulty if the most dominant decay fails to fix the sign of the inequality. This difficulty can be bypassed by switching over to the indirect method discussed below.

The indirect method is applicable to a decaying particle which belongs to a set of correlated particles *having the same actual spin*. Such a set of particles falls into either of the two following categories: (i) a set of particles (of identical actual spin) belonging to a particular representation of a group (be it a global gauge group like $\mathrm{SU}_f(N)$ or local gauge group like a GUT group); and (ii) a set of particles (of identical actual spin) forming a spectroscopy (such as for example, ψ- and Υ-spectroscopy). We first consider the decay of a particle belonging to a set of particles of category (i). For the decays of such a set of particles the following general conclusion holds as shown elsewhere [6,8]: the allowed decays (real or virtual) of all the particles belonging to a particular representation of a group are described by *one and the same* constraint. This fact enables us to specify the constraint for a given decaying particle without any reference to its decay modes if we can somehow manage to ascertain the constraint for some other particle provided both these particles belong to the same representation of a group. To illustrate this point, we consider the gauge bosons belonging to the 24-representation of the SU(5) GUT group. For the reason already mentioned above, the decays (real or virtual) of the twenty four physical gauge bosons, which include Z^0 and γ, must be described by one and the same constraint. Keeping this point in mind, we proceed to specify the constraint for γ^*-decay by considering the decays $\gamma^* \to e^+e^-$, $\mu^+\mu^-$. For the decaying field γ^* we have $d_u = 1$ as evident from Eq. (3) and for the e^+e^- mode $D = d_{e^+} + d_{e^-} = \frac{3}{2} + \frac{3}{2} = 3$ since $d_{e^+} = d_{e^-} = \frac{3}{2}$ which follows from Eq. (1). Obviously, $D = 3$ for the $\mu^+\mu^-$ mode. Therefore, the decay $\gamma^*(d_u = 1) \to e^+e^-$ $(D = 3)$ clearly indicates that the constraint operative in γ^*-decay must be $d_u \leq D$ if we assume that e^+e^- is the dominant mode. The form of the constraint remains the same if the $\mu^+\mu^-$ mode happens to be the dominant one. This constraint must also hold true for the decays of Z^0- and W-bosons as well as Z^{0*} and W^* for the reason stressed earlier. The indirect method for particles of category (ii) has been discussed in earlier papers [6,8,10,12].

3. *Influence of the PD rule on productions of the 5-plet Higgs bosons*

We are now in a position to invoke the PD rule in our ivestigation on the nature of production of the 5-plet Higgs bosons of the HTM in the following decays:

$$Z^0 \to H_5^+ \underbrace{W^{-*}}_{\hookrightarrow l^-\overline{\nu}_l} \quad , \quad Z^0 \to H_5^- \underbrace{W^{+*}}_{\hookrightarrow l^+\nu_l} \quad , \quad Z^0 \to H_5^0 \underbrace{Z^{0*}}_{\hookrightarrow l\bar{l},\, \nu_l\overline{\nu}_l} \tag{A}$$

and

$$Z^0 \to H_5^{++}H_5^{--}, H_5^+H_5^- . \tag{B}$$

Obviously, the nature of production of the Higgs bosons concerned will be influenced by the status of the above mentioned decays in the light of the PD rule. We, therefore, proceed to analyze these decays in the perspective of this rule by recalling that Z^0-decays are described by the constraint $d_u \leq D$. The same rule demands, as manifested in its statement, that only those decay modes of Z^0 can be treated as allowed ones (from the viewpoint of this rule) which are in conformity with the constraint concerned. For convenience of further discussion, we first concentrate on the decays (A). For the decaying vector boson Z^0 we have $d_u = 3$ which follows from Eq. (1). Also for the $H_5^+W^{-*}$ mode, we get $D = d_{H_5^+} + d_{W^{-*}} = 1 + 3 = 4$ since $d_{H_5^+} = 1$ and $d_{W^{-*}} = 3$ as evident from Eq. (2) and Eq. (1), respectively. Taking advantage of these equations, it is easy to check that $D = 4$ for both the modes $H_5^-W^{+*}$ and $H_5^0Z^{0*}$. Clearly, then, the decays $Z^0(d_u = 3) \to H_5^+W^{-*}$ $(D = 4)$, $H_5^-W^{+*}$ $(D = 4)$, $H_5^0Z^{0*}$ $(D = 4)$ are consistent with the constraint $d_u \leq D$ operative in Z^0-decay. These decays, therefore, enjoy the status of allowed ones from the standpoint of the PD rule. We now shift our attention to the decays of off-shell vector bosons: $W^{-*} \to l^-\overline{\nu}_l$, $W^{+*} \to l^+\nu_l$, and $Z^{0*} \to l\bar{l}$, $\nu_l\overline{\nu}_l$. As noted earlier, the decays of Z^0 and W as well as Z^{0*} and W^* are governed by the constraint $d_u \leq D$. We first confine our attention to the decay $W^{-*} \to l^-\overline{\nu}_l$. For the decaying vector boson W^{-*}, we have $d_u = 3$ from Eq. (1). For the $l^-\overline{\nu}_l$ mode, we get $D = d_{l^-} + d_{\overline{\nu}_l} = \frac{3}{2} + \frac{3}{2} = 3$ as $d_{l^-} = d_{\overline{\nu}_l} = \frac{3}{2}$ which follows from Eq. (1). Therefore, the decay W^{-*} $(d_u = 3) \to l^-\overline{\nu}_l$ $(D = 3)$ is allowed by the PD rule as for this decay the above mentioned constraint is clearly satisfied. Proceeding in a similar fashion, one can easily verify that the other decays $W^{+*} \to l^+\nu_l$ and $Z^{0*} \to l\bar{l}$, $\nu_l\overline{\nu}_l$ are also allowed by the same rule. From our above discussion it follows that as the decays $Z^0 \to H_5^+ l^-\overline{\nu}_l$, $H_5^- l^+\overline{\nu}_l$, $H_5^0 l\bar{l}$, $H_5^0\nu_l\overline{\nu}_l$ are allowed by the PD rule, the production modes $H_5^+ l^-\overline{\nu}_l$, $H_5^- l^+\nu_l$, $H_5^0 l\bar{l}$, $H_5^0\nu_l\overline{\nu}_l$ involving a single Higgs boson may occur uninhibited according to the same rule. As a necessary consequence of this, the branching ratio for the decay $Z^0 \to H_5^+ l^-\overline{\nu}_l$, as estimated in Ref. 5, remains unchanged under the action of the PD rule for the reason mentioned above.

Finally, we turn our attention to the pair productions of charged Higgs bosons of the 5-plet via the decays (B). As shown before, $d_u = 3$ for the decaying vector boson Z^0. Also, for the mode $H_5^{++}H_5^{--}$ we have $D = d_{H_5^{++}} + d_{H_5^{--}} = 1 + 1 = 2$ since $d_{H_5^{++}} = d_{H_5^{--}} = 1$ as evident from Eq. (2). Similarly, $D = 2$ for the mode $H_5^+H_5^-$. Consequently, the decays $Z^0(d_u = 3) \to H_5^{++}H_5^{--}(D = 2)$, $H_5^+H_5^-(D = 2)$ fail to satisfy the constraint $d_u \leq D$ which describes the allowed decays of Z^0. These decays are, therefore, forbidden and as such suppressed by the PD rule. As an outcome of this, suppression must necessarily be witnessed in production of the charged pairs $H_5^{++}H_5^{--}$, $H_5^+H_5^-$ in Z^0-decays. It is worthwile mentioning here that the branching ratio of the decay $Z^0 \to H_5^+H_5^-$ has been estimated in Ref. 5 on the implicit assumption that this decay is an allowed one. This is because this decay, although allowed by all the conventional selection rules relevant for weak decays, is *not* allowed by the PD rule (which is valid in all types of decays including weak decays as underlined earlier). This means that the *overall* status of the decay under consideration turns out to be that of a forbidden one. As a result, the effective branching ratio of this decay must fall far short of that estimated in Ref. 5.

Our discussion on the production behaviour of the 5-plet Higgs bosons of the HTM in Z^0-decays remains incomplete unless we touch upon the point relating to their crucial role in experimental searches for these bosons. Needless to emphasize that the feasibility of the detection of a particle is intimately related to its production cross section. In fact, the prospect of experimental observation of a particle is reduced to a great extent if its effective production cross section turns out to be much less than its theoretically expected value. This is really the case for a particle whose production is suppressed for the reason not accounted for by the theory relevant for its production. We have underlined above that the production of the pairs $H_5^{++}H_5^{--}$, $H_5^+H_5^-$ via Z^0-decay must suffer model-independent suppression under the action of the PD rule. As an outcome of this, experimental discoveries of the charged Higgs bosons will be a much harder task than what is generally expected if the production modes $H_5^{++}H_5^{--}$, $H_5^+H_5^-$ are considered for searches of their signatures. In sharp contrast to this, the production modes involving a single Higgs boson (which include $H_5^+ l^-\overline{\nu}_l$, $H_5^- l^+\nu_l$) can offer a convenient platform for the same purpose as these modes do not suffer any suppression at all.

4. *Conclusions*

In summary, we have studied the influence of the pseudo-dimension rule on production of the 5-plet Higgs bosons ($H_5^{++,+,0,-,--}$) of the Higgs triplet model with $\varrho = 1$ in Z^0-decays. It has been shown that the production modes involving a single Higgs boson are expected to occur without any inhibition according to the above mentioned rule. In contrast to this, pair productions of charged Higgs bosons are expected to undergo suppression as demanded by the same rule. These considerations lead us to conclude that the former production modes are much more suitable than the latter ones for experimenatl searches for evidence of the Higgs bosons referred to above.

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PRODUKCIJA PETEROSTRUKIH HIGGSOVIH BOZONA TRIPLETNOG HIGGSOVA MODELA U Z^0 – RASPADU

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Razmotrena je priroda tvorbe peterostrukih Higgsovih bozona u okviru tripletnog Higgsova modela (sa $\varrho = 1$) elektroslabog međudjelovanja u Z^0 – raspadu, uz pretpostavku da mase proizvedenih Higgsovih bozona zadovoljavaju kinematičke uvjete raspada. Primjenjujući pseudo-dimenziono izborno pravilo zaključeno je da je pri tom raspadu stvaranje jednog Higgsova bozona bitno vjerojatnije od stvaranja bozonskog para.