Structure of the Higgs sector and the vertex $Z^0W^{\pm}H^{\mp}$

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The dependence of the tree vertex $Z^0W^{\pm}H^{\mp}$ on the structure of the Higgs sector is analyzed in various models of the electroweak interaction. The theoretical possibility and the feasibility of observing the reaction $e^+e^-\to Z^0\to W^-H^+$ are discussed.

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1. One of the most important problems today is the experimental search for scalar Higgs bosons H, which figure in recent models of the electroweak interaction. It is not by accident that these particles are referred to as elusive. On the one hand, the theory as it exists today does not tell us the masses of these particles or the structure of the Higgs sector; on the other, the predicted cross sections for the production of H bosons are generally very small (see Ref. 1, for example), and it is a rather complicated problem to identify the final state.

An extremely promising reaction in this connection is the joint production of H with Z^0 and $W^{\pm}$ bosons, because of the comparatively large three-boson vertex. In particular, in the case of the neutral boson H^0 much hope is pinned on the reaction $e^+e^-\to Z^0H^0$, whose cross section is comparable to $\sigma(e^+e^-\to\mu^+\mu^-)$ over a broad interval of the mass m_{H^0} (Ref. 2). We should emphasize that the observation of the joint production of H bosons with gauge bosons would simultaneously explain the nature of the scalar particles (and thus the mechanism generating the masses of the intermediate bosons). In models with dynamic symmetry breaking (in the technicolor theories, for example), the analog of the H boson of the bare-bones Weinberg–Salam model has a large mass (~1 TeV). Although comparatively light scalar particles (pseudo-Goldstone bosons) appear in the technicolor theories, the vertices for their interaction with gauge bosons are missing in the tree approximation and thus extremely small. These pseudo-Goldstone bosons are analogous to some of the scalar particles which figure in the standard model with several doublets. The distinctive features of the pseudo-Goldstone bosons can be seen only in details[4] and result from the specific structure of their coupling with fermions, which depends, however, on the particular model.

We know that physical charged scalar particles $H^{\pm}$ appear in models which contain several multiplets of Higgs particles. The hope for observing these scalar particles is pinned primarily on the decay $t\to H^+ + b$ (Refs. 1 and 5); it might also be useful to measure the angular distributions in the reaction[6] $e^+e^-\to H^+H^-$. As in the case of H^0, it would be interesting to study the coupling of the $H^{\pm}$ with the Z^0 and $W^{\pm}$ bosons (the skeletal vertices $W^{\mp}H^{\pm}\gamma$ and $Z^0H^0\gamma$ do not occur because of conserva-

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tion of electric current). It turns out that the vertex $Z^0 W^\pm H^\mp$ depends strongly on the structure of the Higgs sector in the theory. In particular, if nonzero vacuum expectation values arise only for the scalar fields which transform under a doublet representation of the SU(2) group, such a vertex does not arise. It can be shown that this vertex is a measure of just how exotic the Higgs sector is. A study of the transition $Z^0 \to W^\pm H^\mp$ might make it possible to distinguish elementary Higgs scalars from the pseudo-Goldstone bosons of the technicolor series. We will also evaluate the $Z^0 W^\pm H^\mp$ amplitude in a model with right-handed currents.

There are theoretical arguments for a small H^+ mass: $m_{H^+} \lesssim 10$ GeV (Ref. 5). Comparatively light charged H bosons with $m_{H^+} \lesssim 5$–10 GeV are also required[7] when the observed CP violation originates from Higgs Bosons. At $m_{H^+} \lesssim 10$ GeV we might be able to observe the decay $Z^0 \to W^\pm H^\mp$ in (in particular) an e^+e^- collision. At $m_{H^+} > m_Z - m_W$, the $W^\pm H^\mp$ formation would go through a virtual Z^0 boson. The experimental identification of the $W^- H^+$ final state might be aided by the particular features of the decays of W^- and H^+: $W^- \to q(e^-) + \bar{q}(\nu_l), H^+ \to \tau^+(c) + \nu_\tau(s)$. Particularly promising in this regard are the lepton decays of W^-, in which a substantial fraction of the energy is carried off by neutrinos. Near the threshold, the lepton spectra are essentially monochromatic: $E_l \sim m_W/2$.

2. The ordinary version of the standard SU(2) X U(1) model[8] contains only doublets of Higg bosons $\varphi_k = (\varphi_k^{(+)}, \varphi_k^{(0)})$, $k = 1, \ldots, n$; their neutral components generate the vacuum expectation values $\langle \varphi_k^{(0)} \rangle \equiv v_k$. In this case, the $Z^0 W^\pm H^\mp$ vertex does not occur in the tree approximation. It could arise from the following part of the Lagrangian:

$$\sum_{k=1}^{n} | g A^a T^a \varphi_k + \frac{g'}{2} Y_k B \varphi_k |^2 , \tag{1}$$

where T^a $(a = 1, 2, 3)$ are the generators of the $\mathrm{SU}(2)_L$ group. Without any loss of generality we may choose $Y_k = +1$. In this case we find the following expression for the $Z^0 W^- H^+$ vertex:

$$-\frac{g\bar{g}}{\sqrt{2}} Z_\mu W_\mu^- \sum_{k=1}^{n} v_k^* \varphi_k^{(+)} , \tag{2}$$

where $\bar{g} = \sqrt{g^2 + g'^2}$. The combination $\Sigma_{k=1}^n v_k^* \varphi_k^{(+)}$, however, corresponds to a charged Goldstone boson, which goes into making the $W^\pm$ bosons heavier, so that there is actually no physical vertex. The incorporation of higher-order representations of Φ with isospin T and hypercharge Y in the Higgs sector necessarily leads to the appearance of a vertex which is observable in principle[1)]:

$$-\xi m_Z g Z_\mu W_\mu^- H^+ . \tag{3}$$

In general, the dimensionless parameter ξ, which depends on the vacuum expectation values, is a small quantity. As was explained above, we have $\xi \to 0$ in the limit $\langle \Phi \rangle \to 0$. At the same time, the vacuum expectation values $\langle \Phi \rangle$ of the nondoublet fields are probably small, since their growth generally violates the relation $\rho \equiv m_W^2 / m_Z^2 \cos^2\theta_W = 1$ ($\rho_{\mathrm{expt}} = 1.000 \pm 0.015$; Ref. 10). In particular, if an arbitrary real multiplet with $Y = 0$ is introduced into the bare-bones model, we find

$|\xi| \cong \sqrt{|1-\rho|} \lesssim 0.12$. The same restriction holds for the triplet with $Y=2$. We further note that for $T \gg Y$ we have $|\xi| \lesssim \sqrt{|1-\rho|}\sqrt{1+Y^2}$, while for $T=Y/2$ we have $|\xi| \lesssim \sqrt{|1-\rho|}\sqrt{2T-1}$; i.e., $|\xi|$ may become relatively large, although this result would require some extremely exotic representations. We note that some of these representations (for example, the 7-plet with $Y=4$, the 26-plet with $Y=15$, or the 97-plet with $Y=56$) do not violate the relation $\rho=1$ at all, so that there are no restrictions on their vacuum expectation values or thus on the value of ξ.

3. In the bare-bones version of the model based on the $SU(2)_L \times SU(2)_R \times U(1)$ group,[11] the Higgs sector contains the representations (2, 1, 1), (1, 2, 1), (1, 3, 2), (2, 2, 0). After a spontaneous symmetry breaking, the development of a vacuum expectation value for the field (2, 2, 0) gives rise to a tree vertex $Z^0 W^{\pm} H^{\mp}$; ξ turns out to be on the order of the mixing of the right-hand and left-hand Z and W bosons, which is proportional here to the square of the ratio of the vacuum expectation values. At[10] $m_{W_L}/m_{W_R} \lesssim \frac{1}{3}$ we have $|\xi| \lesssim 0.03$. The restrictions on ξ, which result from the incorporation of higher-order representations in the Higgs sector, are essentially the same as the results found for the standard model.

Let us estimate the probability for the decay $Z^0 \to W^- H^+$: $\Gamma(Z^0 \to W^- H^+) = (|\xi|^2 g^2/24\pi)[2+(E_W^2/m_W^2)] \times \sqrt{E_W^2 - m_W^2}$, where $E_W = (m_Z^2 + m_W^2 - m_H^2)/2m_Z$ and $\Gamma(Z^0 \to W^- H^+)/\Gamma(Z^0 \to \mu^+\mu^-) = A|\xi|^2$. For H masses from 4 to 10 GeV, the value of A varies from 1.6 to 0.9. In the case of the technicolor pseudo-Goldstone boson P^+ we have $\Gamma(Z^0 \to W^- P^+)/\Gamma(Z^0 \to W^- H^+) \lesssim |\xi|^{-2}\,(10^{-7}\text{–}10^{-8})$. We thus see that the observation of an appreciable relative probability for the decay of a Z^0 into a W^- and a charged scalar particle would constitute evidence that the Higgs bosons are of an elementary nature and that the Higgs sector has a rather complicated structure. Furthermore, these results raise the hope that a Higgs sector with something more than a bare-bones structure might just present us with such a pleasant surprise as the simultaneous observation of $W^{\pm}$ and $H^{\mp}$ at the peak of a Z^0 boson.

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1) After this paper had been completed, we learned that Grifols and Méndez[9] had made a similar assertion previously. However, the expression, which we find for the vertex $Z^0 W^{\pm} H^{\mp}$, differs from that of Ref. 9 for real Φ with $Y=0$.

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