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The Neutral Higgs Meson in the Standard Electroweak Theory*

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ABSTRACT

Some possible signatures of the neutral Higgs meson H° of the standard electroweak theory are investigated. We find that (1) The polarization measurement of the final fermion pair in $e^{+}e^{-}\rightarrow f\bar{f}$ can give definite signature of H" . and (2) The present known 0^{++} mesons can not be the condidate of H°. We also calculate the cross sections for $\ell^{+}\ell^{-}\rightarrow Z^{\circ}H^{\circ}$, and $\ell^{+}\ell^{-}\rightarrow Z^{\circ}H^{\circ}H^{\circ}$ and find that the Z° angular distribution takes a simple from $A+B\cos^{2}\theta$. Thus the measurement of the Z° angular and the energy distribution can give definite signature of H" .

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I. INTRODUCTION

Nearly, all the predictions of the standard electroweak theory' have been confirmed, experimentally[2], up to the present available energies, except the elusive netural Higgs' meson. The Higgs' scalars are originally introduced in order to generate the particle mess&. In the standard electroweak theory under the unitary gauge only one massive neutral Higgs' meson left. No matter whether it is composite or elementary, it should exist if the standard electroweak theory is the right theory. In this article, we investigate some signatures of the neutial Higgs' meson in the framework of the standard electroweak theory.

We first consider the process of the electron-positron annihilation, into another lepton pairs via the neutral Higgs' meson H°. In this process when $v\rightarrow c$ only the initial electron and positron with the same helicity can annihilate into H°, and only lepton pair with the same helicity can be produced. This is very different from the $e^{-}e^{+}$ annihilation via photon or Z°, in which all lepton pairs have opposite helicity. This means that the polarization meansurement of the final lepton pair will give definite signature of the neutral Higgs' meson. This resonance production of H° and the processes with definite chirality are presented in section 2.

In section 3, we calculate the decay widths of the neutral Higgs' meson into (A) a fermion pair (B), a meson pair and (C) a baryon pair. In section 4, we compare the known scalar mesons with the properties of the neutral Higgs' mesons, and conclude that all the presently known scalar mesons[3] including $\xi(2.2)$[4] can not be the condidate of the neutral Higgs meson. In section 5, we calculate the angular and the energy distributions of the H° prsduction processes: $\ell^+\ell^- \to Z^\circ H^\circ$, $Z^\circ H^\circ H^\circ$ and find that the angular distribution takes a simple form $A + B\cos^2\theta$. Thus the measurement of the angular and the energy distributions can give definite signature of H°. Finally we conclude our work in the last section.

II. ELECTRON-POSITION ANNIHILATION VIA γ, Z° AND H°

In the standard electroweak theory, the electron interacts with the photon γ, Z° and the neutral Higgs' meson H° according to

$$L_{int} = -eA_\mu [\bar{\psi}_L \gamma_\mu \psi_L + \bar{\psi}_R \gamma_\mu \psi_R] + \frac{ie}{\sin\theta_W \cos\theta_W} Z_\mu [(\sin^2\theta_W - \frac{1}{2}) \bar{\psi}_L \gamma_\mu \psi_L +$$

$$\sin^2\theta_W \bar{\psi}_R \gamma_\mu \psi_R] - \frac{m_e}{\sqrt{2}\rho} H^\circ [\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L] \quad (1)$$

where $\psi_L = \frac{1}{2}(1+\gamma_5)\psi$, $\psi_R = \frac{1}{2}(1-\gamma_5)\psi$, and $\rho = [\frac{\sqrt{2}}{4G}]^{1/2}$ with G as the Femi constant. The interaction (1) implies that the photon and the Z° preserve the chirality of the electron, while the neutral Higgs' meson reverses it. Thus in the electron-positron annihilation, the photon and Z° pick up and produce only those fermion pairs with opposite chirality, while the neutral Higgs' meson selects those with the same chirality.

It is well known that when $v \to c$, ψ_L represents the state with negative helicity and ψ_R the state with positive helicity. In this limit, the electron-positron annihilation cross sections are well known. And the fermion pairs coming out via γ and Z° have opposite helicity, while those via H° should have the same helicity. Therefore the polarization measurement of the final fermion pairs can give definite signature of the neutral Higgs' meson. Unfortunately this point seems not properly emphasized, and has not been taken seriously by experimentalists in the search of H°.

When $v < c$, the chirality is no longer the helicity which is the spin component along the direction of motion. For fermions, the positive chirality state ψ_R has a polarization v/c, while the negative chirality state ψ_L has $-v/c$. For antifermions, the polarization changes sign. Therefore for an unpolarized electron-positron annihilation, the final massive lepton pairs with definite chirality have the same polarization $\frac{v}{c}$ or $-\frac{v}{c}$ if the annihilation is via the neutral Higgs' meson, ortherwise they have opposite polarization if the annihilation is via the photon or Z°. If we sum over all possible final chiralities, then from expression (1), we see that the net polarization along the direction of motion vanishes if the annihilation is via H° and γ, and is equal to

$$\frac{\sin^2\theta_W - \frac{1}{4}}{(\sin^2\theta_W - \frac{1}{2})^2 + \sin^4\theta_W} \frac{v}{c} \quad (2)$$

for the fermions if the annihilation is via Z°. This gives a simple way to determine the Weinbery angle θ_W by measurin the longitudinal polarization of the final massive fermion. We note that if $\sin^2\theta_W = 0.25$ then the net longitudinal polarization vanishes.

It is maybe of interest to give the annihilation cross sections which involves definite chiralities. The calculations are straight-forward. The results are

$$\frac{d\sigma}{d\Omega}(e^-_\lambda e^+_{-\lambda} \to \gamma, Z^\circ \to f_{\lambda'}\bar{f}_{-\lambda'})$$

$$= \frac{1}{4}\frac{1}{64\pi^2}\left[\frac{s-4m_f^{\,2}}{s-4m_e^{\,2}}\right]^{1/2}\frac{1}{s}\left|\frac{-Q_f e^2}{s} + \frac{g^2}{\cos^2\theta_W} Q_{e\lambda} Q_{f\lambda'} \frac{1}{s - m_z^2 + i\Gamma_z m_z}\right|^2$$

$$\times \left\{[(s-4m_f^2)(s-4m_e^2)]^{1/2}\cos\theta + \lambda\lambda' s\right\}^2 \qquad (3)$$

where λ and λ' are the chiralities which are 1 for righthand and -1 for lefthand, Q_f is the charge of the fermion, and $Q_{f\lambda}$ is defined through the interaction between fermion and Z°

$$L_{fz} \equiv \frac{ie}{\sin\theta_W \cos\theta_W} Z_\mu \sum_{f,\lambda} Q_{f\lambda}\, \bar{f}_\lambda \gamma_\mu f_\lambda \qquad (4)$$

The value for $Q_{f\lambda}$ is tabulated in Ref. 5. We note that in expression (3), the fermion f can be any lepton or quark except the electron, itself. For the annihilation via H°, we have

$$\frac{d\sigma}{d\Omega}(e^-_\lambda e^+_\lambda \to H^\circ \to f_{\lambda'}\bar{f}_{\lambda'})$$

$$= \frac{1}{4}\frac{1}{64\pi^2}\left(\frac{m_e m_f}{2\rho^2}\right)^2\left[\frac{s-4m_f^2}{s-4m_e^2}\right]^{1/2}\frac{(s-2m_e^2)(s-2m_f^2)}{(s-m_H^2)^2+\Gamma_H^2 m_H^2}\frac{1}{s} \qquad (5)$$

It is isotropic as expected. We note that the factor $\frac{1}{4}$ in expression (3) and (5) come from the average over the initial spins.

III. THE DECAYS OF H°

The neutral Higgs' meson H° of the standard electroweak theory is a scalar meson with the charge conjugation quantum number c = 1. In order to compare H° with known 0^{++} mesons, we first calculate the various decay widths of H°, suitable for comparisions.

Within the framework of the standard electroweak theory, the decay widths of H° decaying into a leptor pair or a quark pair can be easily calculated to be

$$\Gamma(H^\circ \to f\bar{f}) = \frac{G m_f^2 m_H}{4\sqrt{2}\pi}\left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} \qquad (6)$$

where G is the Fermi constant, f represents lepton or quark, and the factor

$$\left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} \qquad (7)$$

represents the threshold effect. When $m_H >> 2\,m_f$, for all possible leptons and quarks, the threshould factor (7) reduces to one and the decay width (6) becomes proportinal to m_f^2.

This mesons that the ratio among the partial widths is equal to the ratio of the mass squared of the final fermion. Since m_H is still unknown and all the theoretical bounds[6] on m_H are tentative, (For example, the existence of any super heavy fermion can reduce the lower bound to very small value) it is better to keep an open mind on the possible values of m_H. In this analyses, we will allow m_H to vary down to 1 GeV. Therefore the threshold factor (7) is generally not negligible. The hadronic decay width of H° is assumed to be equal to

$$\Gamma (H^\circ \rightarrow \text{hadrons}) = \sum_q \Gamma (H^\circ \rightarrow q\bar{q}) \quad (8)$$

where q represents the quark.

The decay widths of the neutral Higgs' meson decaying into the mesons or the baryons can be estimated in the spirit of the Field-Feynman fragmentation model.[7] The simplest cases are the decays of H° into a meson pair (MM) or into a baryon pair ($B\bar{B}$). The decay widths can be estimated as follows

(A) $H^\circ \rightarrow M\overline{M}$

The H° first decays into a quark pair which produces color field. The color field then creates another quark pair which is combined with the previously produced quark pair to form MM pair. In this way, we have

$$\Gamma (H^\circ \rightarrow \pi^+\pi^-) = \Gamma (H^\circ \rightarrow u\bar{u}) \gamma_d \alpha + \Gamma (H^\circ \rightarrow dd) \gamma_u \alpha,$$
$$\Gamma (H" \rightarrow K^+K^-) = \Gamma (H" \rightarrow s\bar{s}) \gamma_u \alpha + \Gamma (H" \rightarrow u\bar{u}) \gamma_s \alpha \quad (9)$$

where γ_q is the probabity of producing $q\bar{q}$ pair from the color field and α is the probability of forming a preudoscalar meson from the $q\bar{q}$ pair. Other decay modes can similarly be written down.

(B) $H^\circ \rightarrow B\bar{B}$

The H° first decays into a quark pair as in (A). But now the color field creates a diquark pair which is combined with the previously produced quark pair to form $B\bar{B}$. In this way, we have

$$\Gamma (H^\circ \rightarrow P\bar{P}) = 2\Gamma (H^\circ \rightarrow u\bar{u}) \gamma_{ud}\bar{\alpha} + \Gamma (H^\circ \rightarrow d\bar{d}) \gamma_{uu}\bar{\alpha},$$
$$\Gamma (H^\circ \rightarrow \Sigma^+\Sigma^-) = 2\Gamma (H^\circ \rightarrow u\bar{u}) \gamma_{us}\alpha + \Gamma (H" \rightarrow s\bar{s})) \gamma_{uu}\bar{\alpha} \quad (10)$$

where $\gamma_{qq'}$ is the probability of producing the diquark pair $qq' - \bar{q}\bar{q}'$ from the colar field and $\bar{\alpha}$ is the probability of forming spin $-\frac{1}{2}$ baryon from the three quark system $(q_1 q_2 q_3)$. Other dedecay modes can be similarly written down.

IIII. H° AND THE KNOWN 0^{++} MESONS

The hadronic decay width of H° is calculated according to the expressions (6) and (8) with various Higgs' masses ranged from 1 GeV to 1 TeV. In the calculations, only the open $q\bar{q}$ channels are considered. The quark masses are taken to be constituent since they are going to form hadrons. We use the following values

$m_u = m_d = 382$ MeV ; $m_s = 510$ MeV

$m_c = 1548$ MeV ; $m_b = 4730$ MeV

The results are given in Table 1. From Table 1, we see that for $m_H < 5$ GeV, Γ (H” → hadrons) $\leqslant 10^{-3}$ MeV.

we also calculate the ratio

$$R = \Gamma(H^\circ \to \pi^+\pi^-)/\Gamma(H^\circ \to K^+K^-) \qquad (11)$$

for $m_H < 5$ GeV by using the expressions (9). In the calculations, we use[7,8] $\gamma_u = \gamma_d = 2/5$, $\gamma_s = 1/5$. The results are given in Table 2, in which the ratios between the leptonic width and the hadronic width are also given.

The present known 0” mesons are given in Table 3. No leptonic modes are observed. By comparision of the Table 1, 2 and 3, we conclude that all the present known 0” mesons, including $\xi(2.2)$[4], can not be the candidate of H” .

TABLE 1 The hadronic decay width of H°

m_H(GeV)	$\Gamma(H^\circ \to$ hadrons)(MeV)
1	1.5×10^{-4}
1.5	a.4 $\times 10^{-4}$
5	3.0×10^{-3}
10	8.4×10^{-2}
30	1.3×10^{-1}
60	2.9×10^{-1}
100	4.8
150	7.5
200	9.9
1000	49.8

IV. THE PRODUCTION OF H°

In this section, we consider the following two H°-production processes: $\ell^+\ell^- \to Z^\circ \to Z^\circ H^\circ$ and $\ell^+\ell^- \to Z^\circ \to Z^\circ H^\circ H^\circ$, where ℓ denotes the lepton. We first derive the corresponding cross sections and then make some discussions. In the calculations, we do not ignore the lepton mass such that the formula derived will be applicable for any leptons, light or heavy.

TABLE 2 The ratios between the H° widths. $R_{\pi/K} = \Gamma(H^\circ \to \pi^+\pi^-)/\Gamma(H^\circ \to K^+K^-)$, etc.

m (GeV)	$R_{\pi/K}$	R_{μ}	$R_{\tau/\mu}$
1		9.0×10^{-2}	0
2	1.03	3.2×10^{-2}	0
3	0.94	2.8×10^{-2}	0
4	0.91	2.7×10^{-2}	2.1
5	0.89	2.6×10^{-2}	7.8

TABLE 3 The known 0^{++} mesons. $R_{\pi/K}$ is ratio between the $\pi\pi$ mode and the KK mode (for χ mesons, only the charged are considered).

0^{++}	Mass (MeV)	Γ_{Tot} (MeV)	$R_{\pi/K}$
S^*	975 ± 4	33 ± 6	3.5
δ	983 ± 2	54 ± 7	
ε	∿ 1300	200 ∿ 600	∿ 9
χ	3415.0±1.0		1.1
ξ	2220 ± 20	30 ± 10 ± 20	

The cross section for the process $\ell^+\ell^- \to Z^\circ \to Z^\circ H^\circ$ is calculated according to the interaction Lagrangian density (1). It is then straightforward to derive the following differential cross section

$$\frac{d\sigma}{d\Omega}(\ell^+\ell^- \to Z^\circ H^\circ) = A + B\cos^2\theta \qquad (12)$$

where θ is the angle between Z° and the incident lepton and

$$A = \frac{1}{(4\pi)^2}\,\frac{G_F^2}{(m_Z^2 - E^2)^2}\,\frac{1}{E^2}\,\frac{k}{p}\Big\{ m_Z^6 [4\sin^4\theta_W E^2 + 2(1-4\sin^2\theta_W)m_\ell^2]$$

$$+ (1-2\sin^2\theta_W)m_\ell^2[m_Z^4(\sin^2\theta_W\epsilon^2 - 2E^2) - 2m_Z^2(E^4 + 2\epsilon^2E^2) + 2\epsilon^2E^4]\Big\} \qquad (13)$$

$$B = -\frac{1}{4\pi^2}\,\frac{G_F^2}{(m_Z^2 - E^2)^2}\,\frac{m_Z^4}{E^2}(1-2\sin^2\theta_W)^2 k^3 p \qquad (14)$$

In the above expressions, G_F is the Fermi constant, k(p) is the magnitude of the Z° (incident electron)'s momentum, E is the total C.M. energy, and ϵ is the energy of Z°. The cross section is then integrated to be

$$\sigma(\ell^+\ell^- \to Z^\circ H^\circ) = 4\pi\,[A + \tfrac{1}{3}B] \qquad (15)$$

From the expression (12), we see that the H° production gives a simple angular distribution to the Z° particle. Therefore the angular distribution measurement can give a definite signature of H° and the mass of the H° can be determined via energy-momentum conservation to be

$$m_H^2 = E^2 - 2E\epsilon + m_Z^2 \tag{16}$$

At the present available energy, the process $e^+e^- \to Z^\circ H^\circ$ is not measurable. But for the future LEP machine, the above process is expected to be observed if m_H is not too large. In order to give a feeling about the event rate, we calculate the cross section (15) for the electron-position annihilation with the total c.m. energy E = 100 GeV. and $m_H = 3$ GeV. The result is equal to 0.037 nb. Since the highest luminosity so far reached is equal to 1.7 x $10^{31}\,cm^2\,sec^{-1}$, the event rate for this luminosity is then equal to 2.26 per hour. The event rate will be even higher if the luminosity increases in the future. This means that the above process is not a rare event for the future LEP experiments, at least for low m_H.

For the process $\ell^+\ell^- \to Z^\circ \to Z^\circ H^\circ H^\circ$, the calculations of the cross sections are lengthy yet straightforward. The additional interaction used takes the following form

$$\frac{e^2}{2(\sin 2\theta_W)^2} \quad H^\circ H^\circ Z_\mu Z_\mu \tag{17}$$

The angular distribution of the final Z° particle is derived to be

$$\frac{d\sigma}{d\Omega} = \bar{A} + \bar{B}\cos^2\theta \tag{18}$$

with

$$\bar{A} = \frac{\pi L}{96}\left\{3CS_4 - 4(E-2m_H)CS_3 - 6A_0S_2 + 12(E-2m_H)A_0S_1\right\}$$

$$\bar{B} = \frac{\pi L}{96}\left\{3DS_4 - 4(E-2m_H)DS_3 - 6B_0S_2 + 12(E-2m_H)B_0S_1\right\} \tag{19}$$

where E is the total C.M. energy, p is the magnitude of the incident lepton momentum and

$$L = \frac{4}{\sqrt{2}(2\pi)^5}\ \frac{1}{pE}\ \frac{m_Z^6 G_F^3}{(E^2 - m_Z^2)^2}$$

$$S_i = \left[\frac{(E-m_H)^2 + m_Z^2 - m_H^2}{2(E-m_H)}\right]^i - m_Z^i$$

$$C = \frac{(1-2\sin^2\theta_W)}{m_Z^6}\left[2\sin^2\theta_W m_\ell^2 M_Z^4 - 2m_\ell^2 m_Z^2 E^2 + m_\ell^2 E^4\right]$$

$$D = -2\,(1-2\sin^2\theta_W)^2\frac{p^2}{m_Z^2} = \frac{B_0}{m_Z^2}$$

$$A_0 = 2\sin^4\theta_W E^2 + (1-4\sin^4\theta_W)m_\ell^2 - \frac{2(1-2\sin^2\theta_W)}{m_Z^2}m_\ell^2E^2 + \frac{(1-2\sin^2\theta_W)}{m_Z^4}m_\ell^2E^4 \tag{20}$$

The energy distribution of the final Z° particle is also derived. The result is

$$\frac{da}{de} = \frac{\pi^2 L}{2}\Big\{(C+\frac{1}{3}D)\epsilon^3 - (E-2m_H)(C+\frac{1}{3}D)\epsilon^2 - (A, +\frac{1}{3}B_0)\epsilon + (E-2m_H)(A_0+\frac{1}{3}B_0)\Big\} \quad (21)$$

where ϵ is the energy of the final Z". The total cross section can then be easily derived from the expression (18) to be of the form

$$\sigma = 4\pi \bar{A} + \frac{47r}{3}\bar{B} \quad (22)$$

This is proved to be identical to the total cross section derived from the expression (21), where the Z° energy lies between

$$m_Z \leqslant \epsilon \leqslant \frac{(E-m_H)^2 + m_Z^2 - m_H^2}{2(E-m_H)} \quad (23)$$

The upper bound in expression (23) is derived from th energy-momentum conservation.

From the expressions (12) and (18), we see that the Z° angular distribution look similar for both processes $\ell^+\ell^- \to Z^\circ H^\circ$ and $\ell^+\ell^- \to Z^\circ HH^\circ$. But when $E >> m_H$, m_Z, we have $\bar{B} > 0$ while B is alway negative. Thus when E is very large, the angular distributions for both processes become quite different. For given total C.M. energy E, the Z° energy for the process $\ell^+\ell^- \to Z^\circ H^\circ$ is unique, while the Z° energy for $\ell^+\ell^- \to Z^\circ H^\circ H^\circ$ follows the distribution (21) which is a polynormial in Z° energy of degree three. Therefore the measurement of the Z° angular and energy distributions can give definite H° signature.

VI. CONCLUSIONS

In this paper, we investigate some possible signatures of H° in the standard ecectroweak theory. We first emphasize that the polarization measurement of the final lepton pair in e^+e^- annihilation can give definite signature of H°, because the lepton pairs coming from 'Y and Z° have opposites helicity, while those from H° have the same helicity. The processes involving definite chiralities are also calculated and given by expressions (3) and (5).

The decay widths of H° into (a) a fermion pair, (b) a meson pair and (c) a baryon pair are calculated and given by expressions (6), (9) and (10). We then use these formula to compare the properties of H° with the known 0" meson including $\xi(2.2)$, and conclude that all the present known 0" meson can not be the candidate of H".

The angular and the enrgy distribution of the Z° paritcle in the H° production processes: $\ell^+\ell^- \to Z^\circ H^\circ$ and $\ell^+\ell^- \to Z^\circ H^\circ H^\circ$, are calculated and given by the expressions (12), (16), (18) and (2 1). From the above expressions we see that the measurement of the Z° angular and energy distributions can give definite signature of H".

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