Concerning the searches for Higgs bosons

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The great successes achieved by the Standard Model (SM) lead us to believe the existence of the Higgs particle. On the other hand, there are many evidences indicate that some unknown dark matter particle must exist in our universe. To identify the Higgs boson as the dark matter particle is difficult in the present SM, the challenge is: the Higgs particle is unstable while the dark matter particle is stable. A solution of this problem is proposed in this paper. We will describe a model in which almost all the predictions made by the present SM remain unchanged but leave two neutral stable Higgs particles, which may be the dark matter particle. Some possible experimental tests of Higgs particle are also suggested in this paper.

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I. INTRODUCTION

One of the main goals of the running Large Hadron Collider (LHC) experiments is to search for the Higgs boson—the last unobserved particle predicted by the Standard Model (SM) [1]. The searches for Higgs bosons had been carried out at LEP $e^+e^-$ collider for many years before the final shutdown. Higgs boson searches have also been carried out at the Tevatron $p\bar{p}$ collider, and will continue at the LHC $pp$ collider, covering masses up to about 1 TeV [2, 3]. The great successes of the SM lead us to believe the existence of the Higgs particle, the question is then: where and how we can discover the Higgs particle? On the other hand, there are many evidences indicate that some unknown dark matter particle must exist in our universe. It is difficult to identify the Higgs boson as the dark matter particle in the present SM because of the obvious reason the Higgs particle is unstable while the dark matter particle is stable. However, after performing a careful analysis of the present SM we find another possibility in which the unstability of the Higgs particle could be avoided, this paper will describe the model in which almost all the predictions made by the present SM remain unchanged but leave two unelectrified stable Higgs particles, which may be the dark matter particle.

II. THE THEORY OF HIGGS FIELD

We will restrict our attention to the first-generation leptons, i.e. the electron $e$ and the electron-type neutrino $\nu_e$. They compose a left-handed doublet and two right-handed singlets when they coupled to gauge fields.

$$L \equiv \begin{pmatrix} \frac{1}{2} (1 - \gamma_5) & \nu_e \\ \bar{e} & \nu_e \end{pmatrix}, \quad \nu_{eR} \equiv \begin{pmatrix} \frac{1}{2} (1 + \gamma_5) \end{pmatrix} \nu_e, \quad e_R \equiv \begin{pmatrix} \frac{1}{2} (1 + \gamma_5) \end{pmatrix} e.$$  

But when the leptons coupled to the Higgs fields, in order to remain the stability of the Higgs particle, we must replace the Yukawa coupling in the present SM with a direct coupling between two leptons and two Higgs. In this case both left-handed leptons and right-handed leptons transform as a singlet. Inspired by the fact that a quark has three different kinds of color and they compose a triplet of color space, we assume that the neutral Higgs particle has two different kinds of weak charge and compose a doublet

$$H(x) = \begin{pmatrix} H_1^0(x) \\ H_2^0(x) \end{pmatrix}. \quad (2)$$

The hypercharge of the member of the doublet is then

$$\frac{Y}{2} = Q - T_3 = \begin{pmatrix} 0 & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{pmatrix}.$$  

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The Higgs fields \( H_1^0(x) \) and \( H_2^0(x) \) have different hypercharge! How the Higgs doublet transform under the \( U(1)_Y \) group? This is not a problem, we can choose \( \frac{Y}{2} = \frac{1}{3} \) or \( \frac{Y}{2} = -\frac{1}{2} \) for the \( U(1)_Y \) group element \( U(1)_Y(\theta) = \exp[-i\theta \frac{Y}{2}] \) for the doublet, the effect by doing so is leaving an additional phase factor to \( H_1^0(x) \) or \( H_2^0(x) \), which can be absorbed by the phase of the \( H_1^0(x) \) or \( H_2^0(x) \) field without changing anything physical. In the following discussion, we choose \( \frac{Y}{2} = \frac{1}{2} \) for the Higgs doublet.

Now, we discuss the electroweak phase transition. Imagining at the beginning of the universe, shortly after the Big Bang, the universe is in a state of high temperature and high density. In this case the gauge fields and leptons are independent partners from the Higgs particle, or in other words, there is no interaction between Higgs particle and gauge fields(or leptons). Because particles gain their mass through interacting with the Higgs particle, we say that at the beginning of the universe, all particles(except the Higgs particle itself) are massless. An equivalent description of the universe expands, the temperature of the universe will drop to a critical temperature \( T_c \) at the beginning of the universe, all particles(except the Higgs particle) or in other words, there is no interaction between Higgs particle and independent partons from the Higgs particle, or in other words, there is no interaction between Higgs particle and leptons become coupled to the Higgs particle and gain their mass. The equivalent description is at low energy, the presence of a “non-zero Higgs field” gives the particles their mass. Supposing the system is near the critical temperature \( T_c \), it is natural that we choose the Higgs particles’s wave function \( H(x) \) as the order parameter for this phase transition, then \( |H(x)|^2 = \bar{H}(x)H(x) = H_1^0(x)^2 + H_2^0(x)^2 \) can be interpreted as the Higgs particles’s density \( n_H(x) \). According to Landau’s phase transition theory, we expand the invariant Lagrangian as

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i\bar{L} \gamma^\mu (\partial_\mu - ig^\mu \frac{1}{2} W_\mu^a + ig^\mu \frac{1}{2} B_\mu^a)L + i\bar{e}_R \gamma^\mu (\partial_\mu + ig' B_\mu) e_R \\
-\alpha(T) |H(x)|^2 - \beta(T) |H(x)|^4 + \frac{1}{2} |\partial_\mu H(x)|^2 - \frac{1}{4} m^2 |H(x)|^2 - \frac{1}{2} m^2 |H(x)|^2 - \frac{\lambda}{4} |H(x)|^4 \\
- G_{eL}(\bar{e}_L H(x) e_R + \bar{e}_R H(x) e_L) - G_{\nu_L}(\bar{\nu}_L H(x) \nu_R + \bar{\nu}_R H(x) \nu_L). \tag{4}
\]

Where \( m \) is the mass of Higgs particle. When \( \frac{1}{2} m^2 + \alpha(T) < 0 \), the system has the lowest energy at

\[
|H(x)|^2 = \bar{H}(x)H(x) = H_1^0(x)^2 + H_2^0(x)^2 = v^2, \tag{5}
\]

with

\[
v = \sqrt{-\frac{m^2 + 2\alpha(T)}{\lambda + 4\beta(T)}}. \tag{6}
\]

The constant \( v \) is called the vacuum expectation value of the field. In Eq.(4), the Higgs-gauge fields interaction is contained in the terms

\[
\mathcal{L}_{Hg} = \frac{1}{2} |\partial_\mu H(x)|^2 - i g^\mu \frac{1}{2} W_\mu^a H(x) - ig^\mu \frac{1}{2} B_\mu H(x)|^2 - \frac{1}{2} m^2 |H(x)|^2 - \frac{1}{4} |H(x)|^4 \\
= \frac{1}{2} \partial_\mu H_1^0(x) \cdot \partial^\mu H_1^0(x) + \frac{1}{2} \partial_\mu H_2^0(x) \cdot \partial^\mu H_2^0(x) - \frac{1}{2} m^2 (H_1^0(x)^2 + H_2^0(x)^2) \\
- \frac{1}{2} (H_1^0(x)^2 + H_2^0(x)^2)^2 + \frac{1}{8} H_1^0(x)^2 (g' B_\mu + g W_\mu^3) (g' B_\mu + g W_\mu^3) + \frac{1}{8} H_2^0(x)^2 (g' B_\mu - g W_\mu^3) (g' B_\mu - g W_\mu^3) \\
+ \frac{1}{8} g^2 H_1^0(x)^2 (W_\mu^1 - g W_\mu^2) (W_\mu^1 + g W_\mu^2) + \frac{1}{8} g^2 H_2^0(x)^2 (W_\mu^1 + g W_\mu^2) (W_\mu^1 - g W_\mu^2) + \frac{1}{8} g^2 H_1^0(x)^2 (W_\mu^2 + g W_\mu^1) (W_\mu^2 - g W_\mu^1). \tag{7}
\]

We redefine the gauge fields as

\[
W_\mu^- = \frac{1}{\sqrt{2}} (W_\mu^1 + i W_\mu^2), \quad W_\mu^+ = \frac{1}{\sqrt{2}} (W_\mu^1 - i W_\mu^2), \\
Z_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (g' B_\mu \pm g W_\mu^3), \quad A_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (g B_\mu \mp g' W_\mu^3) \tag{8}
\]

and replacing \( |H(x)|^2 = H_1^0(x)^2 + H_2^0(x)^2 \) everywhere by \( v^2 \). We get the mass of recombined gauge fields

\[
M_W = \frac{g}{2} v, \quad M_Z = \frac{\sqrt{g^2 + g'^2}}{2} v, \quad M_A = 0. \tag{9}
\]
These predictions are as same as that of the present SM[1]. The interaction between leptons and gauge fields also remains intact comparing with the present SM[1]. So this new mode is in accordance with all the well-established electroweak precision tests(EWPT) carried out mainly at the Large Electron Positron(LEP) collider at CERN.

What are the new predictions made by this model? one is the neutrino mass. The last four terms in Eq.(4) immediately tell us the electron mass and the neutrino mass

\[ M_e = G_e v^2, \quad M_{\nu e} = G_{\nu e} v^2, \tag{10} \]

which means that the electron and the neutrino have the same mass generation mechanism in this model, their mass difference is due to they interact with the Higgs particle to different degrees. The other new prediction comes from the last term in Eq.(7), which means that although part of the original gauge fields recombined into massive gauge particles \( W^\pm, Z^0 \) and massless photon \( A_\mu \) after the electroweak symmetry breaking(EWSB), there is still a part of original, massless gauge fields \( B_\mu, W_1^\mu \) remain in the universe. They interact only with the Higgs particles and change the weak charge carried by the Higgs particle just like a gluon interact with a quark and change the quark’s color in quantum chromodynamics(QCD).

The most important new prediction made by this mode is there existing two kinds of stable, neutral Higgs particles \( H_0^1 \) and \( H_0^2 \) in the universe, they have the same mass and identical interaction. These stable, massive particle, interacting weakly with the ordinary matter[4] and do not interact with the photon at all, are in complete accord with the dark matter particle, so it is natural to assume that the Higgs particle and the dark matter particle are the same particle. Basing on this assumption, we estimate the mass of the Higgs particle in the next section.

### III. THE MASS OF HIGGS PARTICLE

The mass of the Higgs particle \( m \) in Lagrangian[4] is introduced as a free parameter in this model. However, we can roughly estimate the mass of the Higgs particle based on the assumption that the Higgs particle and the dark matter particle are the same particle. Supposing when the electroweak phase transition occurs at \( T = T_c \) at a preliminary stage of the Big Bang, the universe’s energy density \( \rho \) is dominated by that of Higgs particles. Then we have \( \rho \simeq \rho_H = a T_c^4 \), where \( a \) is the radiation constant. On the other hand, \( \rho_H = \frac{N \bar{\varepsilon}}{\sqrt{3} \pi R^3} \), here \( \bar{\varepsilon} \approx 3 k_B T_c \) is the average energy of the Higgs particle. So we have

\[ \frac{N \bar{\varepsilon}}{\sqrt{3} \pi R^3} = a T_c^4. \tag{11} \]

At present day, \( \rho_H \) has become \( \rho_H = \frac{N m}{R^3} \), where \( m \) is the mass of Higgs particle. Define \( \rho_H / \rho_0 = \bar{P} \), \( \rho_0 \) is present day energy density of the universe, then \( \bar{P} \) represents the ratio of the total energy of the universe contributed by the Higgs particles. Therefore we have

\[ \frac{N m}{\sqrt{3} \pi R_0^3} = \rho_0 \bar{P}. \tag{12} \]

Combining Eq.(11) and Eq.(12), and assuming the total number of the Higgs particle \( N \) remain unchanged, we get

\[ m = \left( \frac{R_0}{R} \right)^3 \frac{\rho_0 \bar{P}}{a T_c^4} \times 3 k_B T_c, \tag{13} \]

where the subscript 0 indicates present day values.

The standard Big Bang model gives \( R_0/R \sim 10^{14} \). However, considering the universe undergoes an electroweak phase transition at \( T = T_c \) controlled by the Higgs particle, that would lead to an exponential expansion

\[ R_2 = R_1 e^{H(t_2-t_1)} \tag{14} \]

with

\[ H = \sqrt{\frac{8 \pi G_N}{3} a T_c^4}, \tag{15} \]

where \( R_1 \) and \( R_2 \) are the scale parameters at times \( t_1 \) and \( t_2 \), the above value of \( R_0/R \) should be modified. Substituting the EWSB temperature \( T_c \sim 10^{15} \) K into Eq.(15), we obtain

\[ H = \sqrt{\frac{8 \pi G_N}{3} a T_c^4} \simeq 10^9 \text{s}^{-1}, \tag{16} \]
which means the electroweak phase transition occurs at about $10^{-9}$ s. Assuming this phase transition end at $10^{-8}$ s, it gives

$$R_2/R_1 = e^{|t_2-t_1|} = e^9 = 8.1 \times 10^3. \quad (17)$$

So the modified $R_0/R$ will be $R_0/R \sim 8.1 \times 10^{17}$. The following parameters have been used in our numerical calculation:\[5\]:

$$R_0/R = 8.1 \times 10^{17}, a = 7.57 \times 10^{-16} \text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-4}, T_c = 10^{15} \text{K},$$

$$\rho_0 = 1.88 \times 10^{-26} \text{Kg} \cdot \text{m}^{-3}, k_B = 1.38 \times 10^{-23} \text{J} \cdot \text{K}^{-1}, h_0 = 0.72. \quad (18)$$

The Big Bang nucleosynthesis(BBN) theory tells us that ordinary matter contribute to about 5% of the energy density of the universe $\rho_0$. If the dark energy does not exist, we may take $P = 0.95$. Substituting the above parameters into Eq.\[13\], we get $m = 151 \text{GeV}$. The mass of Higgs particle is sensitive to the ratio $R_0/R$, by changing the ratio $R_0/R$ from $7.1 \times 10^{17}$ to $9.1 \times 10^{17}$, we find the mass of Higgs particle is in the range of $102 \text{GeV}$ to $214 \text{GeV}$. If the dark energy does exist and contribute to about 74% of the total energy density of the universe\[5\], in this case we may take $P = 0.21$. Repeating the above process of calculation, we find the mass of Higgs particle will be in the range of $23 \text{GeV}$ to $47 \text{GeV}$. The uncertainty of the EWSB temperature $T_c$ will also bring a large uncertainty for the Higgs particle mass. Considering the main uncertainty comes from the ratio $R_0/R$, there might be large uncertainties in our predictions for the Higgs particle mass. Eventually, the accurate value of the mass of Higgs particle should be determined by experiments, and some possible experimental tests of Higgs particle will be proposed in the next section.

### IV. POSSIBLE EXPERIMENTAL TESTS OF HIGGS PARTICLE

The Higgs-electron coupling term $\mathcal{L}_{He} = -G_e(H^0_i(x)^2 + H^0_i(x)^2)e\bar{e}$ contained in the Lagrangian\[4\] immediately tells us that the Higgs particle can be produced directly by the following process

$$e^+ + e^- \rightarrow H^0_i + \bar{H}^0_i, \quad (i = 1, 2) \quad (19)$$

where $\bar{H}^0_i$ are anti-Higgs particles. Are the Higgs particle and its anti-particle the same particle? Imagining at the beginning of the universe, Higgs particles are in a state of high temperature and high density, if $H^0 = \bar{H}^0$, they must annihilate rapidly, so it is reasonable to assume that the Higgs particle is not its own anti-particle, i.e. $H^0 \neq \bar{H}^0$.

Now we compute the unpolarized cross section for $e^+e^- \rightarrow H^0\bar{H}^0$, to the lowest order.

Considering an electron with 4-momentum $p_1 = (E, \vec{p})$ collide with a positron with $p_2 = (E, -\vec{p})$, in the center of mass frame, we obtain

$$\frac{d\sigma}{d\Omega}(e^+e^- \rightarrow H^0\bar{H}^0) = \frac{G^2_e|\vec{p}_H||\vec{p}_H|}{128\pi^2E^2}, \quad (20)$$

where $|\vec{p}_H|$ is the momentum of Higgs particle. Integrating over $d\Omega$, and neglecting the mass of the electron, we find the total cross section

$$\sigma(e^+e^- \rightarrow H^0\bar{H}^0) = \frac{G^2_e}{32\pi} \sqrt{1 - \frac{m_H^2}{E^2}}, \quad (21)$$

where $m_H$ represents the mass of Higgs particle. Considering the fact that the Higgs particle has two different kinds of weak charge, finally we obtain

$$\sigma(e^+e^- \rightarrow H^0\bar{H}^0) = 2\sigma(e^+e^- \rightarrow H^0_1\bar{H}^0_1) = \frac{G^2_e}{16\pi} \sqrt{1 - \frac{m_H^2}{E^2}}. \quad (22)$$

Of course the cross section is zero for $E < m_H$. In the high-energy limit where $E \gg m_H$, the cross section will reach a maximal value $\frac{G^2_e}{16\pi}$. Substituting $M_e = 0.5\text{MeV}$\[2\] and $\nu = 246\text{GeV}$ into Eq.\[10\], we get $G_e = 8.26 \times 10^{-9}\text{GeV}^{-1}$. Therefore the maximal cross section for $e^+e^- \rightarrow H^0\bar{H}^0$ will be $\sigma_{\text{max}} = \frac{G^2_e}{16\pi} \approx 5.3 \times 10^{-46}\text{cm}^2$. The predicted production cross section is very small, a lots of efforts should be made before the final experimental confirmation of Higgs particle.
The process\cite{19} also provide a good way for detecting indirectly the Higgs particle that existing in the universe. Supposing the process $e^+e^- \rightarrow H^0 \bar{H}^0$ occur at somewhere in the universe, the produced anti-Higgs particle $\bar{H}^0$ will move freely within the universe. When they pass through a region where the Higgs particle is sufficient clumping(such as in the galactic center), there is a possibility that they and Higgs particles with higher energy annihilating into $e^+e^-$ again, the produced $e^+$ and $e^-$ will have a higher energy and result in an excess of the normal cosmic electrons and positrons spectrum. Recently, Chang et al. reported an excess of galactic cosmic-ray electrons at energies of about $300$-$800$GeV\cite{6}, which could arise from the annihilation of Higgs and anti-Higgs particles.

The elastic scattering of a Higgs particle off a nucleus in a detector

$$H^0 + N \rightarrow H^0 + N$$

(23)

can be used for directly detecting the Higgs particle that existing in the universe. The Higgs-Quark interaction is given by

$$\mathcal{L}_{Hq} = -G_q H^0 \bar{H}^0 \bar{q}q.$$  

(24)

Setting $M_u = M_d = 4$MeV\cite{5} and $\nu = 246$GeV, we get $G_u = 6.61 \times 10^{-8}$GeV$^{-1}$. So the expected cross section for a Higgs particle scattering off a target nucleus should be proportional to $G_u^2$, i.e. $\sigma(H^0 + N \rightarrow H^0 + N) \propto G_u^2 \approx 1.7 \times 10^{-42}$cm$^2$, which may pass the quite strong constraints on the elastic scattering cross section with nucleons of potential dark matter candidates imposed by many direct dark matter detection experiments\cite{7}. These results confirm once again our assumption that the Higgs particle and the dark matter particle are the same particle.

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