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Fermion Masses in a Strong Yukawa Coupling Model

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For strong enough Yukawa coupling the electroweak standard model fermion finds it energetically advantageous to transform itself into a bound state in the hedgehog background of the Higgs field in the semiclassical approximation. By considering that the bound states give the masses for the lepton and quark, it is found that all fermion masses can be described by the strongly Yukawa coupling constants which tend to a unitary constant.

1. INTRODUCTION

The standard model of the electroweak interaction (Glashow, 1961; Weinberg, 1967; Salam, 1968) has received a great deal of phenomenological support. The gauge boson and fermion structure of the model has been confirmed to a high degree of accuracy, although there is very little phenomenological support for the Higgs sector of the theory. The most difficult part of this theory to understand is the Yukawa sector. It contains a large number of free parameters that must be adjusted by hand to obtain a realistic spectrum of particles and mixings. In this sector, there are no explanations for the three-generation structure of leptons and quarks. Recently, it was reported that the top quark mass is much bigger than the masses of other leptons and quarks (Abe *et al.*, 1995). There is a large mass hierarchy among three-generation fermions. One can try to understand these features of the standard electroweak theory by the use of some of the successful ideas of this theory or by entirely new ideas.

The basic dynamical degrees of freedom in the electroweak theory are the two-component Weyl fields with definite helicities. The gauge interactions conserve helicity and do not mediate between the system of the left-handed

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and that of the right-handed fermions. The only bridge between these two systems is provided by the hypothetical scalar Higgs boson, which couples to the various fermions with a strength proportional to their masses. The lepton and the quark in the standard model are massless before the spontaneous symmetry breaking (SSB) and their masses are produced by the Yukawa coupling after the SSB. The standard picture in the model with SSB involves a vacuum expectation value (VEV) for the Higgs fields which are constant over the whole space. The fermion mass values are given by introducing Yukawa coupling constants, and the masses are proportional to the Yukawa coupling constants. On the other hand, it is expected that the presence of a fermion with strong coupling to the Higgs field can modify the standard picture. As the Yukawa coupling increases, the Higgs field around a fermion tends to go over from a uniform spatial configuration to a hedgehog configuration (Johnson *et al.*, 1987; Soni *et al.*, 1989; Kahana *et al.*, 1984; Birse and Banerjee, 1985). The uniform configuration leads to a fermion mass which increases linearly with the coupling constant, while the hedgehog configuration gives a decreasing mass.

The existence of two possible configurations means that one can get the same mass value in both the weakly Yukawa coupling phase and the strongly Yukawa coupling phase. To describe the mass spectrum of the lepton and the quark in the weakly coupling phase, we must introduce nine hierarchical Yukawa coupling constants which vary about from 10^{-6} to 1.0. In this paper, alternatively, we shall consider the consequences of having a strongly Yukawa coupling phase take the place of the standard picture for the fermion sector in the Weinberg–Salam model. It is found that all the lepton and quark masses can be described by the strongly Yukawa coupling constants, which tend to a unitary constant.

The strongly coupled fermion-Higgs sector of the standard model has been investigated by Johnson and Schechter (1987) and Soni *et al.* (1989), who exploit the analogy between the strong Yukawa coupling theory and the chiral linear σ-model. They follow Kahana *et al.* (1984), who work in the context of the strong interaction. In this paper we will focus on some features of this scheme for the strong Yukawa coupled standard model from a different point of view. We change the strength of Yukawa coupling in the standard electroweak theory and show that the fundamental ground state of the fermion-Higgs system is not the trivial ground state given by the uniform spatial Higgs field, but is the nontrivial ground state with hedgehog configuration of the Higgs field. The nontrivial ground states give the masses to the leptons and quarks.

Throughout this paper we work in the classical approximation, i.e., we neglect the radiative corrections due to the boson loops and the contribution of the Dirac sea to the energy of the system. The question of whether these effects are important is beyond the present scope. On the other hand, the large Yukawa constants in the standard model cannot be included without violating vacuum stability (Huang, 1979; Politzer and Wolfram, 1979). However, the problem may be overcome by introducing new physics in the TeV region, for example, supersymmetric theories. We will discuss these problems at the end of the paper.

2. BRIEF REVIEW OF WEINBERG–SALAM MODEL

We first give a brief review of the electroweak standard model. The model contains left-handed and right-handed Weyl fermion fields, $SU(2)_L \times U(1)$ gauge fields A^a_μ and B_μ, and a complex Higgs doublet Φ. The Lagrangian of the model is given by $\mathcal{L} = \mathcal{L}_b + \mathcal{L}_f$. The bosonic Lagrangian is

$$\mathcal{L}_b = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 \tag{1}$$

where $F^a_{\mu\nu}$ and $G_{\mu\nu}$ are the $SU(2)_L$ and $U(1)$ field strength tensors, respectively. The fermionic Lagrangian in the chiral representation reads

$$\begin{aligned} \mathcal{L}_f = {} & \bar{\psi}_L i\gamma^\mu D_\mu \psi_L + \bar{u}_R i\gamma^\mu D_\mu u_R + \bar{d}_R i\gamma^\mu D_\mu d_R \\ & - f_U(\bar{\psi}_L \tilde{\Phi} u_R + \bar{u}_R \tilde{\Phi}^\dagger \psi_L) - f_D(\bar{\psi}_L \Phi d_R + \bar{d}_R \Phi^\dagger \psi_L) \end{aligned} \tag{2}$$

where ψ_L denotes the left-handed doublet (u_L, d_L), u_R and d_R are the right-handed singlets, and $\tilde{\Phi} = i\tau_2 \Phi^*$. Here we use (u, d) to represent the (up, down) lepton pair and quark pair. In order to discuss the strong Yukawa coupling model in the following, we introduced the right-handed neutrino to make the small Dirac mass neutrino.

The $SU(2)_L$ gauge symmetry is spontaneously broken due to the nonvanishing VEV v of the Higgs field,

$$\langle \Phi \rangle = -\frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{3}$$

leading to the gauge boson W and Z masses and Higgs mass:

$$M_W = \frac{1}{2} g_2 v, \qquad M_Z = \frac{1}{2} (g_1^2 + g_2^2)^{1/2} v, \qquad M_H = v\sqrt{2\lambda} \tag{4}$$

where g_1 and g_2 are the $U(1)$ and $SU(2)$ gauge coupling constants, respectively, and we take $v = 246.0$ GeV. When the Higgs field develops the VEV v, we see that the Higgs field configuration takes the form of a spatially uniform field. The fermions then acquire masses through their Yukawa couplings f_U and f_D:

$$m_U = f_U \frac{v}{\sqrt{2}}, \qquad m_D = f_D \frac{v}{\sqrt{2}} \tag{5}$$

The masses of three-generation leptons and quarks in the Weinberg–Salam model are described by the following Yukawa coupling constants:

$$\begin{aligned} f_{\nu_e} &< 2.93 \times 10^{-11}, & f_e &= 2.94 \times 10^{-6} \\ f_u &= 2.87 \times 10^{-5}, & f_d &= 5.75 \times 10^{-5} \\ f_{\nu_\mu} &< 1.55 \times 10^{-6}, & f_\mu &= 6.07 \times 10^{-4} \\ f_c &= 7.47 \times 10^{-3}, & f_s &= 1.15 \times 10^{-3} \\ f_{\nu_\tau} &< 1.78 \times 10^{-4}, & f_\tau &= 1.02 \times 10^{-2} \\ f_t &= 1.01 \times 10^{+0}, & f_b &= 2.47 \times 10^{-2} \end{aligned} \tag{6}$$

where we have taken the approximate values for $m_u = 5$ MeV, $m_d = 10$ MeV, $m_s = 200$ MeV, $m_c = 1.3$ GeV, $m_b = 4.3$ GeV, and $m_t = 176$ GeV. We see that the Yukawa coupling constants are weak and unorganized over a wide range. A large hierarchy appears in the Yukawa coupling constants.

3. STRONG YUKAWA COUPLING MODEL

Instead of weak Yukawa coupling in the Weinberg–Salam model, let us consider the case of strong Yukawa coupling. We will compare its prediction with the ground-state energy estimated in a semiclassical manner. Since the Higgs field gives the mass of the fermions, we can neglect the gauge degree of freedom with $A^a_\mu = B_\mu = 0$ in the Weinberg–Salam model. By a simple redefinition of Higgs fields

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi_2 + i\pi_1 \\ \sigma - i\pi_0 \end{pmatrix} \tag{7}$$

and fermion fields $\psi = \psi_L + \psi_R$, where ψ_R stands for u_R and d_R, we can write the Lagrangian $\mathcal{L}$ as $\mathcal{L} = \mathcal{L}_\sigma + \mathcal{L}'$, with

$$\mathcal{L}_\sigma = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \pi)^2 + \bar{\psi}\gamma^\mu \partial_\mu \psi - g\bar{\psi}(\sigma + i\gamma_5 \pi \cdot \tau)\psi - U(\sigma, \pi) \tag{8}$$

where

$$U(\sigma, \pi) = \frac{\lambda}{2}[\sigma^2 + \pi^2 - v^2]^2 \tag{9}$$

and

$$\mathcal{L}' = g'[i\pi_0\bar{\psi}(1 - \gamma_5)\psi + \bar{\psi}\tau_3(\sigma + i\pi \cdot \tau)\psi] \tag{10}$$

where $g = (f_U + f_D)/2\sqrt{2}$, $g' = (f_U - f_D)/2\sqrt{2}$, and $\mathcal{L}_\sigma$ is the σ-model Lagrangian. In the strong Yukawa coupling model, we may assume that the difference of the strongly Yukawa coupling constants for the up-type and down-type leptons and quarks is small (top and bottom quarks as well). If the strongly Yukawa coupling constants are big enough, then we have $g >> g'$. It is very reasonable to make an approximation negecting the term in (10).[2] In the following we will see that in the strong coupling model all the strongly Yukawa coupling constants tend to a unitary constant and g' tends to zero. So in what follows we shall then as a simplification neglect $\mathcal{L}'$, leaving us with $\mathcal{L} = \mathcal{L}_\sigma$.

3.1. Hedgehog Configuration and Radial Equations

There is no guarantee that the classical solution (3) gives the lowest possible ground-state energy in the fermion sector. In the semiclassical approximation we include only the valence fermion and we treat the (σ, π) fields as classical. We consider the hedgehog solution, for which the chiral fields have the form, in terms of the fields,

$$\sigma(x) = \sigma(r), \qquad \pi(x) = \pi(r)\hat{\mathbf{r}} \tag{11}$$

with $\hat{\mathbf{r}} = \mathbf{r}/r$. The pion field then has a dipole shape whose space orientation is coupled to the isospin orientation.

With chiral fields of the form (11), the Dirac equation of fermions admits an s-state solution of the form

$$\psi(x) = \frac{1}{\sqrt{4\pi}}\begin{pmatrix} G(r) \\ i(\sigma \cdot \hat{\mathbf{r}})F(r)\end{pmatrix}\chi_h \tag{12}$$

where χ_h is a state in which the spin and isospin of the fermion couple to zero as $(\sigma + \tau)\chi_h = 0$. Taking the ansatz of (11) and (12) and minimizing (8) produces the following coupled nonlinear equations:

$$\frac{1}{r}\frac{d^2}{dr^2}[r\sigma(r)] = \frac{\partial U}{\partial \sigma} - \frac{g^2}{4\pi}[G^2(r) - F^2(r)]$$

$$\frac{1}{r}\left(\frac{d^2}{dr^2} - \frac{2}{r^2}\right)[r\pi(r)] = \frac{\partial U}{\partial h} + \frac{g^2}{2\pi}G(r)F(r) \tag{13}$$

[2] In the Weinberg–Salam model, this approximation is problematic for top and bottom quarks. However, in the strong Yukawa coupling model, this problem is absent.

$$\frac{dF(r)}{dr} + \left[\frac{2}{r} - g\pi(r)\right]F(r) + [\omega + g\sigma(r)]G(r) = 0$$

$$\frac{dG(r)}{dr} + g\pi(r)G(r) + [-\omega + g\sigma(r)]F(r) = 0.$$

The quantity ω is the eigenvalue of the spinor $\psi(x)$ and the radial fermion wave functions are normalized to $\int r^2\, dr\, [F^2(r) + G^2(r)] = 1$.

These equations are supplemented by the following boundary conditions:

$$\sigma(r) \to c_1, \quad \pi(r) \to 0, \quad G(r) \to c_2, \quad F(r) \to 0, \quad \text{as} \quad r \to 0 \qquad (14)$$

$$\sigma(r) \to -v, \quad \pi(r) \to 0, \quad G(r) \to 0, \quad F(r) \to 0, \quad \text{as} \quad r \to \infty$$

where c_1 and c_2 are arbitrary constants. These express the fact that the physical vacuum is recovered at infinity. In this 'physical' vacuum the fermions are free Dirac particles of mass gv, and chirality is spontaneously broken.

The hedgehog solution is a self-consistent solution in the sense that, when fermions occupy an orbital of the form (12), the equations in (13) for the chiral fields admit a solution of the form (11). The energy E of the system can be written in the form

$$E = \omega + 2\pi \int_0^\infty r^2\, dr \left\{\left(\frac{d\sigma(r)}{dr}\right)^2 + \left(\frac{d\pi(r)}{dr}\right)^2 + \frac{2}{r^2}\pi^2(r)\right\}$$

$$+ 2\pi\lambda \int_0^\infty r^2\, dr\, [\sigma^2(r) + \pi^2(r) - v^2]^2 \qquad (15)$$

A state will be bound if its energy E is lower than the mass gv of one free fermion as $E/gv < 1$; a fermion orbital is bound and it decays exponentially at large distance if its energy eigenvalue ω is such that $|\omega| < gv$. In the strong coupling model, we would consider that the bound state gives the mass for the fermion. The size and the energy scale in such a way that once a bound state is found with an appropriate value of g, one can make the energy increase and the size decrease proportionally with v.

3.2. Soluble Model

Before discussing the solution of the coupled set of equations (13), it is instructive to consider a soluble model on the chiral circle approximation. When the constant λ in the Lagrangian (8) is large enough, the minimum energy occurs for chiral fields restricted to the chiral circle $\sigma^2(r) + \pi^2(r) = v^2$. In this situation it is possible to parametrize the chiral fields by a chiral angle $\theta(r)$:

$$\sigma(r) = v \cos\theta(r), \qquad \pi(r) = v \sin\theta(r) \qquad (16)$$

When one fermion fills an orbital of energy ω, the energy (15) of the system can be expressed in terms of the chiral angle as follows:

$$E = \omega + 2\pi v^2 \int_0^\infty r^2\, dr \left\{ \left(\frac{d\theta(r)}{dr} \right)^2 + \frac{2}{r^2} \sin^2\theta(r) \right\} \tag{17}$$

It is easy to establish that the equations for the $\sigma(r)$ and $\pi(r)$ fields in (13) admit solutions which behave as $\theta(r) \to r - n\pi$ as $r \to 0$ and $\theta(r) \to 1/r^2$ as $r \to \infty$. Let us consider a soluble model in which the chiral angle $\theta(r)$ takes a 'trial' form $\theta(r) = -\pi(1 - r/R)$ for $r < R$ and $\theta(r) = 0$ for $r > R$ as carried out by Kahana *et al.* (1984), corresponding to the choice $n = 1$. The accuracy of this model is assessed in a self-consistent calculation, and it proves quite adequate for a discussion of the physics.

A numerical study of the Dirac equations in (13) with the linear form of the chiral angle has been carried out by Kahana *et al.* (1984). The energy eigenvalue ω is well described by the expression

$$\omega = \frac{3.12}{R} - 0.94gv \tag{18}$$

valid in the range $2 < R < 12$. By substituting the expression (18) for ω and the linear form of the chiral angle into (17), we obtain a schematic expression for the energy of the system as a function of R:

$$E = \frac{3.12}{R} - 0.94gv + 2\pi v^2 \left(1 + \frac{\pi^2}{3} \right) R \tag{19}$$

This equation may be considered as an effective mass formula for the system.

The equilibrium value of R is the value which minimizes the energy (19). One finds $R = 0.34/v$, and the minimum energy is then given by

$$E_{\min} = v(18.33 - 0.94g) \tag{20}$$

The coupling constant g in this model must remain in the range $9.5 < g < 19.5$ to make $E_{\min} < gv$ for the bounded system and $E_{\min} > 0$ for the energy to be nonnegative.

We see that, as the coupling constant g increases, the Higgs field around a fermion tends to go over from a uniform spatial configuration to a hedgehog configuration which gives a decreasing mass with increasing g. We think that the lepton and quark masses are given by the hedgehog configuration of the Higgs field and not by the usual uniform configuration (3) in the Weinberg–Salam model. According to this idea, the energy of the bound state is just the fermion mass, $m_f = E_{\min}$. From equation (20), we find that the fermion mass depends linearly on the coupling constant $g = (f_U + f_D)/2\sqrt{2}$, so we can obtain the values of the strongly Yukawa coupling constants f_U and f_D from the up-type and down-type fermion masses, respectively. The hedgehog configurations of the Higgs field give the masses of the three-generation fermions from the following strongly Yukawa coupling constant y_i (i for leptons and quarks):

$$y_i = \frac{1}{0.94}(18.33\sqrt{2} - f_i) \tag{21}$$

where f_i is the usual Yukawa coupling constant in equation (6). The y_i are given by

$$\begin{aligned} y_{\nu_e} &> 27.572998, & y_e &= 27.572996 \\ y_u &= 27.572969, & y_d &= 27.572938 \\ y_{\nu_\mu} &> 27.572998, & y_\mu &= 27.572354 \\ y_c &= 27.565053, & y_s &= 27.571776 \\ y_{\nu_\tau} &> 27.572810, & y_\tau &= 27.562148 \\ y_t &= 26.498531, & y_b &= 27.546723 \end{aligned} \tag{22}$$

It is found that the quantitative differences in these Yukawa coupling constants appear after the decimal point, except for the top quark; these Yukawa coupling constants tend toward a unitary constant. While the values in (22) depend on the accuracy of the calculation, the results do not qualitatively depend on the particular choice for VEV v or the calculation accuracy.

3.3. Self-Consistent Calculation

In order to obtain more exact results for the strongly Yukawa coupling constant, we solve numerically the nonlinear differential equations (13) for the eigenvalue ω under the boundary conditions (14) for the bound state. Integration of the set of equations (13), with normalization to one fermion, was performed with the aid of the program COLSYS (Ascher *et al.*, 1979).

In Fig. 1 we show the total energy of the system (15) as a function of the Yukawa coupling constant for one bound fermion and for several values of the Higgs mass (the Yukawa coupling constant f can be related to coupling constant g as $f = \sqrt{2}g$). We see that for a given Higgs mass, there exists a critical value of the Yukawa coupling constant above which the fermion can form a stable bound state (as a nontopological soliton) (Friedberg and Lee, 1977) which is lower in energy than the normal mass of one free fermion. These results agree with those of Nolte and Kunz (1993) and Petriashvili (1992). For a given f, the energy of the bound state (soliton) increases

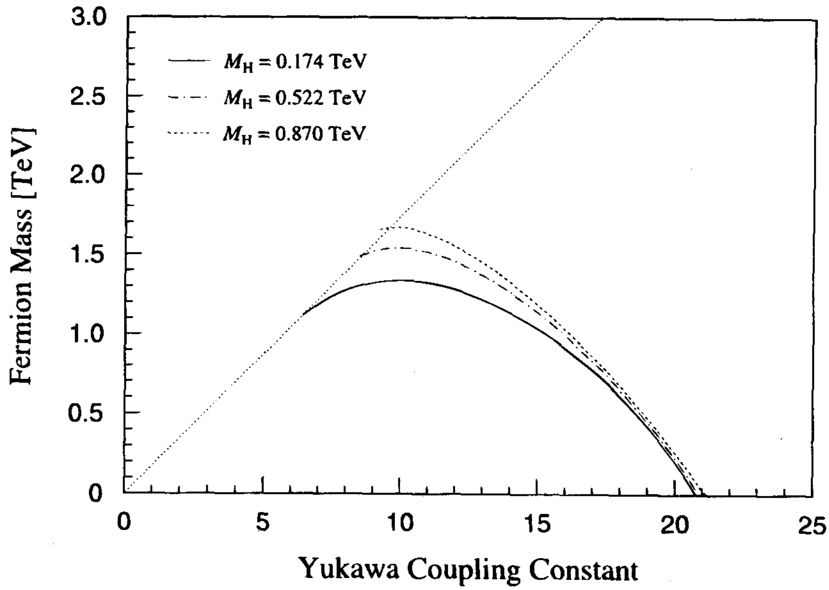

Fig. 1. The bound-state energy (fermion mass) as a function of the Yukawa coupling constant for Higgs mass M_H = 0.174 TeV (solid curve), M_H = 0.522 TeV (dot-dashed curve), and M_H = 0.870 TeV (dashed curve) for one bound fermion. The dotted line represents the usual Yukawa coupling case.

monotonically with the Higgs mass. The energy of the bound state becomes negative for the Yukawa coupling constant $f \sim 21.0$ for the Higgs masses considered. This value gives the upper bound for the Yukawa coupling constant.

As in the soluble model, we think that the bound states give the lepton and quark masses. From (15) we see that the energy of the bound state (soliton) depends on both the Yukawa coupling constant f and the Higgs self-coupling constant λ; thus the fermion mass also depends on both f and M_H. This is different from the standard Weinberg–Salam picture in which the fermion mass can be described by the Yukawa coupling constant alone. In Fig. 1, we see that in the strong Yukawa coupling region ($f \sim 20.0$), the dependence of the fermion mass on f (or g) is approximately linear. As in the soluble model, we can obtain the values of f_U and f_D from the up-type and down-type fermion masses, respectively. The strongly Yukawa coupling constants for the leptons and the quarks are given as follows, where we take $M_H = v/\sqrt{2} = 0.174$ TeV:

$$y_{\nu_e} > 20.789611, \qquad y_e = 20.789611$$

$$y_u = 20.789595, \qquad y_d = 20.789577$$

$$y_{\nu_\mu} > 20.789611, \qquad y_\mu = 20.789236 \qquad (23)$$
$$y_c = 20.784979, \qquad y_s = 20.788911$$
$$y_{\nu_\tau} > 20.789502, \qquad y_\tau = 20.783310$$
$$y_t = 20.118602, \qquad y_b = 20.774090$$

These strongly Yukawa coupling constants tend to a unitary constant, similar to the case in the soluble model, but with a smaller value. Due to the numerical accuracy, the results presented above are not the final values of the Yukawa coupling constants for leptons and quarks, although they do not depend qualitatively on the numerical accuracy.

In Fig. 2 we show the radial functions for the bound state (soliton) with Yukawa coupling constant $y_e = 20.789611$ for electron mass in the case of $M_H = 0.174$ TeV. We see that the fermion is localized in a small region of the space, while the Higgs field approaches its VEV, where $\sigma(r) \to -v$ and $\pi(r) \to 0$, much more slowly. We can define the mean-square radius of the bound state as

$$r_0 = \sqrt{\langle r^2 \rangle}, \qquad \langle r^2 \rangle = \int_0^\infty r^4\, dr\, [G^2(r) + F^2(r)] \qquad (24)$$

The typical radius of the bound state for the lepton and the quark is $r_0 \sim$

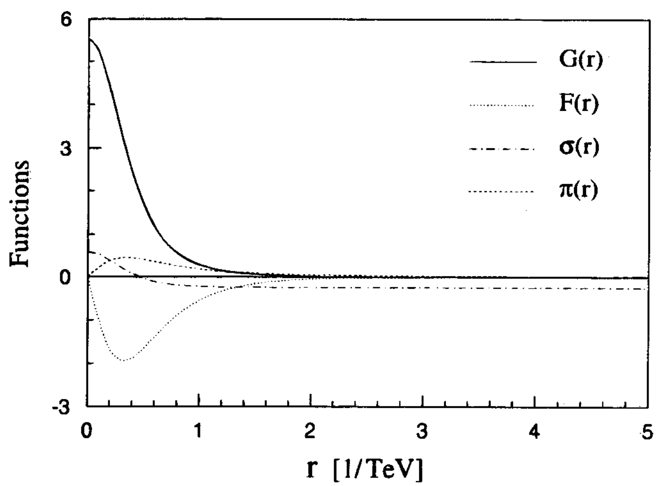

Fig. 2. The fermion field functions $G(r)$ (solid curve) and $F(r)$ (dotted curve) and Higgs field functions $\sigma(r)$ (dot-dashed curve) and $\pi(r)$ (dashed curve) of the bound state (soliton) for the electron as a function of the distance r for $M_H = 0.174$ TeV and Yukawa coupling constant $f = 20.789611$.

0.67/TeV with $M_H = 0.174$ TeV. This value is within the limiting value of recent experimental data (Particle Data Group, 1996). The typical intrinsic energy scale in this strong coupling model is $M_0 = yv/\sqrt{2} \sim 3.6$ TeV. This leads to the interesting possibility of probing the size of leptons and quarks in the next generation of colliders.

As shown in Fig. 2, the hedgehog configuration of Higgs fields [$\sigma(r)$, $\pi(r)$] obviously appears in a region of small distance (smaller than 1.0/TeV) and tends to a uniform configuration at large distances (much bigger than 1.0/TeV). On the other hand, the electroweak gauge symmetry is broken at the energy scale of about 100 GeV (at the distance of 10.0/TeV), where the hedgehog configuration of the Higgs field is close to the normal vacuum configuration (3). So the strong coupling model produces almost the same W and Z masses as the Weinberg–Salam model. However, there is a slight difference from the Weinberg–Salam model due to the fact that the field $\pi(r)$ is not exactly zero in the region of 100 GeV. It should be possible to look for this difference in current experiments.

4. CONCLUDING REMARKS

We have described the lepton and quark masses associated with the electroweak standard model when it carries a strongly coupled fermion–Higgs sector. Within the semiclassical approximation (at the tree level), we have shown that all the masses of leptons and quarks can be given by the strongly Yukawa coupling constants, which tend toward a unitary constant. On the other hand, in the strong coupling model, the W and Z masses produced by the hedgehog configuration of the Higgs field show almost no change. The fermion masses depend slightly on the mass of the Higgs boson at the tree level.

The strong coupled fermion–Higgs bound state (soliton) may be unstable with regard to quantum radiative corrections (Anderson *et al.*, 1990; Bagger and Naculich, 1991). This possible quantum instability should be a common problem in non-point models for leptons and quarks. It is due to the fact that the resulting bound states have sizes which are so much smaller than their Compton wavelengths. This fact is only understandable dynamically if there exists an approximate symmetry which forces certain bound states to have nearly zero mass. On the other hand, the strong Yukawa coupling in the standard model will violate vacuum stability (Huang, 1979; Politzer and Wolfram, 1979) due to radiative corrections, so we should improve the standard model with new physics in the TeV region. In order to stabilize the bound states for the fermion and Higgs vacuum structure against quantum effects, new symmetry should be introduced into the standard model, possibly supersymmetry. In the supersymmetric theories, the radiative corrections due to fermions and bosons cancel miraculously, stabilizing any mass hierarchies that exist and the Higgs vacuum structure. Although there are some problems for the strong Yukawa coupling approach to the fermion mass at the quantum level in the standard model, we stress that the strong Yukawa coupling approach is applicable all spontaneous symmetry-breaking theories, such as the supersymmetric standard model, SUSY-GUT. So we believe that the strong Yukawa coupling approach may be self-consistent at the quantum level in the supersymmetric standard model.

One of the fundamental questions in particle theory is that of the generation structure of quarks and leptons. There are no explanations for this problem in the standard model. The composite models address this problem through quark and lepton substructure in which the generation replication at higher mass scales is explained by the existence of excited levels of the fermionic bound states. In the strong Yukawa coupling model, leptons and quarks are fermion–Higgs bound states (solitons) in the TeV region (energy scale about 3.6 TeV). This offers a new possibility to solve the fermion generation problem. The generations might be considered as excitations of the fermion–Higgs bound states in the strong Yukawa coupling model.

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