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THE TOP QUARK MASS IN A SUPERSYMMETRIC STANDARD MODEL WITH DYNAMICAL SYMMETRY BREAKING

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ABSTRACT

Dynamical symmetry breaking in the supersymmetric standard model is catalyzed by a Nambu-Jona-Lasinio mechanism involving the top quark multiplet. The resulting low energy theory is precisely that of the minimal supersymmetric standard model, but with specific mass relations for the top quark, composite Higgs scalars and their supersymmetric partners. Exploiting the compositeness condition for the Higgs multiplet, these masses are determined using renormalization group techniques.

The increasing experimental lower bound on the top quark mass, which is presently at 60 GeV, has led several authors[1][2] [3][4] to speculate that top quark self interactions, operating at a high energy scale Λ, may be of sufficient strength to trigger the formation of a top quark condensate. This in turn provides for the dynamical breakdown of the electroweak symmetry, without the necessity of fundamental scalars. The interaction, however, generates a scalar $\bar{t}t$ bound state with the quantum numbers of the Higgs boson. At energies far below the compositeness scale Λ, this Higgs bound state behaves as an independent dynamical degree of freedom. The resulting low energy theory is just the standard model but with specific conditions relating the top quark and composite Higgs boson masses to the electroweak and compositeness scales.

The Higgs compositeness condition takes the form of the vanishing of its wavefunction renormalization factor at scale Λ: $Z_h(\mu^2) \to 0$ as $\mu \to \Lambda$. The top quark mass is then determined as a function of Λ by solving the renormalization group equations of the standard model while implementing the compositeness condition. Integration of the one-loop renormalization group equations [2] subject to the compositeness condition leads, for a given Λ, to a unique physically acceptable renormalization flow trajectory. For $\Lambda \approx 10^{15}$GeV, the trajectory gives a top quark mass, $m_t \approx 231$GeV, while the composite Higgs boson has mass $m_{higgs} \approx 258$ GeV. As discussed by Bardeen, Hill and Lindner [2], the numerical value of the top quark mass is controlled by the quasi-infrared fixed point[5] of the renormalization group equation for the top quark Yukawa coupling.

To model the dynamics responsible for the top quark condensation [2][3], a BCS or Nambu-Jona-Lasinio (NJL) mechanism[6] was proposed to act at the compositeness scale. The Lagrangian at scale Λ is taken as (neglecting masses small compared to m_t)

$$\mathcal{L}_\Lambda = \mathcal{L}_{kinetic} + G(\bar{q}_L t_R)(\bar{t}_R q_L), \tag{1}$$

with $\mathcal{L}_{kinetic}$ the usual gauge invariant fermion and gauge boson kinetic terms of the standard model. Using a large N_C approximation, a self-consistent calculation of the top quark mass yields the gap equation

$$G^{-1} = \frac{N_C}{8\pi^2}\left[\Lambda^2 - m_t^2 \ln\left(\frac{\Lambda^2}{m_t^2}\right)\right]. \tag{2}$$

To insure that m_t is of the order of the electroweak scale and not the much larger compositeness scale, it is necessary to fine tune G so that $G^{-1} \approx \frac{N_C}{8\pi^2}\Lambda^2$. The presence of the quadratic divergence and associated gauge hierarchy as well as the requisite fine tuning is the usual one encountered in the standard model. In the present context, however, its appearence is restricted to the gap equation. The imposition of the gap equation leads in turn to the emergence of the bound state Higgs scalar and the standard model as the low energy effective Lagrangian.

One approach which has been advocated to ameliorate the gauge hierarchy problem in the usual standard model is to make the model supersymmetric. The supersymmetric (SUSY) standard model is free from quadratic divergences as a consequence of the softened ultraviolet behavior resulting from the cancellation between boson and fermion loops (no-renormalization theorem). In addition, the extra degrees of freedom due to the SUSY reduces the effects of the strong gauge interaction relative to those of the Yukawa interaction in the running of the top Yukawa coupling. As such the position of the quasi-infrared fixed point is lowered and consequently so should the value of the top quark mass. In the present letter, we investigate a minimal SUSY standard model, without fundamental Higgs multiplets, in which the condensation of the top quark multiplet dynamically breaks the electroweak symmetry. For clarity of presentation, we shall ignore all quark and lepton multiplet masses other than the top quark. Their effects can be included in a straightforward manner.

To implement the symmetry breaking, we use an SU(3)×SU(2)×U(1) invariant (softly broken) supersymmetric Nambu-Jona-Lasinio interaction[7] [8] in addition to the gauge couplings of the SUSY standard model. The action at scale

Λ thus takes the form

$$\Gamma_\Lambda = \Gamma_{YM} + \int dV \left[\bar{Q}e^{2V_Q}Q + T^C e^{-2V_T}\bar{T}^C + B^C e^{-2V_B}\bar{B}^C\right](1 - \Delta^2\theta^2\bar{\theta}^2)$$

$$+G\int dV \left[(\bar{Q}\bar{T}^C)e^{2V_H}(QT^C)\right](1 - 2\Delta^2\theta^2\bar{\theta}^2), \tag{3}$$

where $Q = \binom{T}{B}$ is the SU(2) doublet of top and bottom quark chiral superfield multiplets and T^C (B^C) is the SU(2) singlet charge conjugate top (bottom) quark SUSY chiral multiplet. Γ_{YM} is the usual SUSY gauge field kinetic energy terms, while the quark multiplets interact with the SUSY SU(3)$\times$SU(2)$\times$U(1) gauge fields

$$V_Q = g_3 G^a \frac{1}{2}\lambda^a + g_2 W^i \frac{1}{2}\sigma^i + \frac{1}{6}g_1 Y$$

$$V_T = g_3 G^a \frac{1}{2}\lambda^a + \frac{2}{3}g_1 Y$$

$$V_B = g_3 G^a \frac{1}{2}\lambda^a - \frac{1}{3}g_1 Y. \tag{4}$$

The color singlet, SU(2) doublet composite chiral field QT^C appearing in the NJL term interacts with

$$V_H = g_2 W^i \frac{1}{2}\sigma^i - \frac{1}{2}g_1 Y. \tag{5}$$

Finally, Δ^2 provides the explicit soft SUSY breaking scale which arises from an underlying supergravity[9], with the higher dimension composite fields QT^C feeling twice the breaking strength as the individual Q or T^C fields. In addition, it is assumed that the net hypercharge in the fundamental theory vanishes so that no bare or induced Fayet-Iliopoulos term is present for the U(1) hypercharge field Y.

Including the explicit soft SUSY breaking effects, the pure chiral massive top multiplet propagator is[10]

$$i < 0|T\left(T(1)T^C(2)\right)|0 >= \int \frac{d^4p}{(2\pi)^4} e^{ip(x_1-x_2)} e^{-(\theta_1\sigma^\mu\bar\theta_1-\theta_2\sigma^\mu\bar\theta_2)p_\mu}$$

$$\times \left[\frac{m_T}{p^2+m_T^2+\Delta^2}\right]\left[(\theta_1-\theta_2)^2 - 2\theta_1\theta_2\frac{\Delta^2}{(p^2+m_T^2)}\right], \tag{6}$$

while the mixed propagator takes the form

$$i < 0|T\left(T(1)\bar T(2)\right)|0 >= \int \frac{d^4p}{(2\pi)^4} e^{ip(x_1-x_2)} e^{-(\theta_1\sigma^\mu\bar\theta_1+\theta_2\sigma^\mu\bar\theta_2)p_\mu}$$

$$\times \left[\frac{1}{p^2+m_T^2+\Delta^2}\right]\left[e^{2\theta_1\sigma^\mu\bar\theta_2 p_\mu} + \frac{2\theta_1\sigma^\mu\bar\theta_2 p_\mu\Delta^2}{p^2+m_T^2} - \theta_1^2\bar\theta_2^2\Delta^2\right]. \tag{7}$$

The dynamically generated top quark mass is determined self consistently using the Schwinger-Dyson equation to leading order in N_C which is displayed in Figure 1. Using the chiral propagator of equation (6) one finds

$$m_T = -iGN_C \int^\Lambda \frac{d^4p}{(2\pi)^4}\frac{2\Delta^2 m_T}{(p^2+m_T^2)(p^2+m_T^2+\Delta^2)}. \tag{8}$$

The massive solution then yields the gap equation

$$G^{-1} = \frac{N_C\Delta^2}{8\pi^2}\left[(1+\frac{m_T^2}{\Delta^2})\ln\left(\frac{\Lambda^2}{m_T^2+\Delta^2}\right) - \frac{m_T^2}{\Delta^2}\ln\left(\frac{\Lambda^2}{m_T^2}\right)\right]. \tag{9}$$

It is clear from equation (8) that if there is no explicit SUSY breaking so that Δ vanishes, then the Schwinger-Dyson equation is satisfied only by the trivial solution $m_T = 0$ and there is no mass generation. This is a consequence of the SUSY no-renormalization theorem[11]. Moreover, the dependence on the compositeness scale Λ is only logarithmic. The presence of the supersymmetry has replaced the quadratic dependence on Λ by that of the SUSY breaking scale Δ. We shall see that consistent solutions to the SUSY NJL model exist with Δ of the order of the electroweak scale. Consequently, the fine tuning problem has been eliminated.

To facilitate the construction of the effective low energy theory, it proves convenient to introduce supersymmetric Lagrange multiplier chiral superfields, H and H', and to recast the action of equation (3) in the form

$$\Gamma_\Lambda = \Gamma_{YM} + \int dV \left[\bar{Q}e^{2V_Q}Q + T^C e^{-2V_T}\bar{T}^C + B^C e^{-2V_B}\bar{B}^C\right](1 - \Delta^2\theta^2\bar{\theta}^2)$$

$$+ \int dV \bar{H}e^{2V_H}H(1 - 2\Delta^2\theta^2\bar{\theta}^2)$$

$$- \int dS(m_0 H'H - g_{T_0}H'QT^C) - \int d\bar{S}(m_0\bar{H}\bar{H}' - g_{T_0}\bar{T}^C\bar{Q}\bar{H}'). \qquad (10)$$

Application of the Euler-Lagrange equations for H and H' gives

$$m_0 H = g_{T_0}(QT^C)$$

$$m_0 H' = \frac{\bar{D}\bar{D}}{-4}\left[\frac{g_{T_0}}{m_0}(\bar{Q}\bar{T}^C)e^{2V_H}(1 - 2\Delta^2\theta^2\bar{\theta}^2)\right], \qquad (11)$$

which when substituted into equation (10) reproduces the original action (3) provided we identify $G = \frac{g_{T_0}^2}{m_0^2}$. We see from equation (11) that H and H' are composite chiral superfields. H is a color singlet, SU(2) doublet and carries hypercharge $-\frac{1}{2}$, while H' has the charge conjugate quantum numbers. Clearly H and H' have precisely the quantum numbers of the two Higgs multiplets required in the minimal SUSY standard model.

In addition to the action of equation (10), a gauge invariant kinetic term for H' will also get induced. Evaluating the contribution displayed in Figure 2 using the mixed propagator of equation (7) yields the action piece $Z_{H'} \int dV\, H' e^{-2V_H} \bar{H}'(1 + 2\Delta^2\theta^2\bar{\theta}^2)$, where

$$Z_{H'} = \frac{g_{T_0}^2 N_C}{16\pi^2} \ln\left(\frac{\Lambda^2}{\mu^2}\right) \tag{12}$$

and μ is a normalization scale. As $\mu \to \Lambda$, $Z_{H'}$ vanishes and the H' composite dissassociates. On the other hand, at low energies far below Λ, H' acts as an independent dynamical degree of freedom and its propagation must be included in the low energy effective action. It is important to note that the soft SUSY breaking term induced for H' is opposite in sign to that of the H field. This drives the electroweak symmetry breakdown in the effective theory. (An analogous situation occurs in the case of radiative electroweak breaking[12] in the SUSY standard model.) With the inclusion of the composite Higgs fields, the dynamics at the low energy scale M_Z is governed by the minimal (softly broken) SUSY standard model action

$$\Gamma_Z = \Gamma_{YM} + \int dV \left[\bar{Q}e^{2V_Q}Q + T^C e^{-2V_T}\bar{T}^C + B^C e^{-2V_B}\bar{B}^C\right](1 - \Delta^2\theta^2\bar{\theta}^2)$$

$$+ \int dV\, \bar{H} e^{2V_H} H(1 - 2\Delta^2\theta^2\bar{\theta}^2)$$

$$+ \int dV\, H' e^{-2V_H} \bar{H}'(1 + 2\Delta^2\theta^2\bar{\theta}^2)$$

$$- \int dS(mH'H - g_T H'QT^C) - \int d\bar{S}(m\bar{H}\bar{H}' - g_T \bar{T}^C \bar{Q}\bar{H}'). \tag{13}$$

In obtaining this action we have rescaled the H' field by $H' \to \frac{1}{\sqrt{Z_{H'}}} H'$ and have defined $g_T = \frac{1}{\sqrt{Z_{H'}}} g_{T0}$, $m = \frac{1}{\sqrt{Z_{H'}}} m_0$ so that $G = \frac{g_{T0}^2}{m_0^2} = \frac{g_T^2}{m^2}$.

The vacuum structure and mass spectrum of the low energy theory are determined as usual from the low energy effective potential[13]

$$V = \frac{1}{2}D_Y^2 + \frac{1}{2}D_{W^i}^2 + \frac{1}{2}D_{G^a}^2 + \bar{F}_H F_H + F_{H'}\bar{F}_{H'}$$

$$+2\Delta^2(\bar{A}_H A_H - A_{H'}\bar{A}_{H'}), \tag{14}$$

in conjunction with the auxiliary field equations of motion

$$D_Y = \frac{1}{2}g_1(\bar{A}_H A_H - A_{H'}\bar{A}_{H'})$$

$$D_{W^i} = g_2(A_{H'}\frac{1}{2}\sigma^i\bar{A}_{H'} - \bar{A}_H\frac{1}{2}\sigma^i A_H)$$

$$D_{G^a} = 0$$

$$\bar{F}_H = mA_{H'}$$

$$\bar{F}_{H'} = mA_H. \tag{15}$$

Writing $H = \binom{H_0}{H_-}$ and $H' = (H'_0, \quad H'_+)$, the vacuum expectation values of H and H' are given by

$$<0|H|0> = \frac{1}{\sqrt{2}}\binom{v}{0}$$

$$<0|H'|0> = \frac{1}{\sqrt{2}}(v', \quad 0), \tag{16}$$

and the ground state expectation value of the energy is

$$<0|V|0> = \frac{1}{2}(m^2 - 2\Delta^2)v'^{\,2} + \frac{1}{2}(m^2 + 2\Delta^2)v^2 + \frac{1}{32}(g_1^2 + g_2^2)(v'^{\,2} - v^2)^2. \tag{17}$$

Choosing $2\Delta^2 > m^2$, the potential minimum is realized by $v = 0$ and

$$\frac{1}{8}(g_1^2 + g_2^2)v'^{\,2} = (2\Delta^2 - m^2). \tag{18}$$

The SUSY Higgs mechanism results in $W^\pm$ and Z boson masses having their usual standard model values

$$M_Z^2 = \frac{(g_1^2 + g_2^2)}{4} v'^{\,2} \qquad\qquad M_W^2 = M_Z^2 \cos\theta_W . \tag{19}$$

Defining $e = g_1 \cos\theta_W = g_2 \sin\theta_W$ and the fine structure constant $\alpha = \frac{e^2}{4\pi}$, the potential minimum condition becomes $m^2 = 2\Delta^2 - \frac{1}{2}M_Z^2$. There remain three neutral and two charged massive Higgs scalars $\frac{1}{\sqrt{2}}(A_{H_0'} + A^\dagger_{H_0'}), A_{H_0}(A^\dagger_{H_0}), A_{H\pm}$ with masses squared M_Z^2, $2m^2(2m^2)$, $(2m^2 + M_W^2)$, respectively. The residual higgsino fields are the neutral $\psi_{H_0'}$ and the neutral $\eta = \frac{m\psi_{H_0} + iM_Z\lambda_Z}{\sqrt{m^2+m_Z^2}}$, with mass $\sqrt{m^2 + M_Z^2}$ and the charged $\psi_{H_+'}$ and $\chi_- = \frac{m\psi_{H_-} + i\sqrt{2}M_W\lambda_{W_-}}{\sqrt{m^2+2M_W^2}}$ with mass $\sqrt{m^2 + 2M_W^2}$.

A rough prediction for the top quark mass in the large N_C SUSY NJL model can be extracted by using the expression for Z_H' given in equation (12). So doing we find

$$m_T = \frac{1}{\sqrt{2}} g_T v' = \frac{1}{\sqrt{2}} \frac{g_{T_0}}{\sqrt{Z_{H'}}} v' = \frac{4\pi}{\sqrt{2}} \frac{v'}{\sqrt{\ln\frac{\Lambda^2}{\mu^2}}}, \tag{20}$$

where $v' \simeq 246$ GeV is the electroweak scale. For a compositeness scale of $\Lambda \simeq 10^{15}$ GeV, this gives $m_T \simeq 164$ GeV. In obtaining this value, we have set $\mu \simeq m_T$, the result being insensitive to this choice. This estimate corresponds to the contribution of the top quark multiplet bubble sum only. A more precise determination of m_T including all interactions of the SUSY standard model will be presented shortly.

Prior to doing that, however, we note that within the bubble sum approximation, we can also extract the value of the SUSY breaking scale Δ and hence the mass of the scalar top quark SUSY partner which is given by $\sqrt{m_T^2 + \Delta^2}$. Employing the condition for the potential minimum, equation (18), in conjunction with the gap equation (9) for $G^{-1} = \frac{m^2}{g_T^2}$, and the above determined top quark mass, we find that the SUSY breaking scale Δ satifies the equation

$$\ln\left(\frac{m_T^2}{\mu^2}\right) + \left(1 + \frac{m_T^2}{\Delta^2}\right)\ln\left(1 + \frac{\Delta^2}{m_T^2}\right) = \frac{1}{4}\frac{M_Z^2}{\Delta^2}\ln\left(\frac{\Lambda^2}{\mu^2}\right). \tag{21}$$

For $m_T \simeq \mu \simeq 164$ GeV, $\Lambda \sim 10^{15}$ Gev, and using $M_Z = 91$ GeV, this yields $\Delta \simeq 260$ GeV. Here Δ depends very sensitively on m_T. Thus consistent solutions to the SUSY NJL model exist with Δ and m_T roughly of the order of the electroweak scale when the compositeness scale is many orders of magnitude larger. The model requires no fine tuning to achieve this hierarchy of scales.

The values for m_T and Δ which we have thus far extracted are somewhat crude in that they arise from a summation of only the top quark multiplet loops. We have seen, however, that at energies far below the compositeness scale Λ, the Higgs multiplet develops gauge invariant kinetic terms in addition to their Yukawa couplings and the model reduces to the full SUSY standard model. As such, we can utilize the low energy SUSY standard model renormalization group equations, along with the compositeness condition $Z_{H'} \to 0$ as $\mu \to \Lambda$, to determine more precisely the top quark mass as a function of the compositeness scale Λ and the SUSY breaking scale Δ. Note that in making this determination of m_T, we do not need to identify the specific dynamical mechanism by which the Higgs multiplet is bound. It proves convenient [2] to rescale the induced Higgs field H' by the running top Yukawa coupling $g_T(\mu^2)$ of the SUSY standard model so that $H' \to \frac{1}{g_T(\mu^2)}H'$. So doing, the wavefunction renormalization constant is $Z_{H'}(\mu^2) = \frac{1}{g_T(\mu^2)}$ and the compositeness condition translates into a diverging running top Yukawa coupling at scale Λ. Defining the scaling variable $t = \ln\left(\frac{\mu}{M_Z}\right)$, the one-loop renormalization group equations for the SUSY standard model take the form [12][14]

$$16\pi^2\frac{d}{dt}g_T = g_T\left(6g_T^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{9}g_1^2\right)$$

$$16\pi^2\frac{d}{dt}g_3 = -3g_3^3$$

$$16\pi^2 \frac{d}{dt} g_2 = g_2^3$$

$$16\pi^2 \frac{d}{dt} g_1 = 11 g_1^3. \tag{22}$$

In addition, the value of the gauge couplings at the scale M_Z are taken as $g_1^2(M_Z) = 0.127$, $g_2^2(M_Z) = 0.425$ and $g_3^2(M_Z) = 1.44$. Ignoring the SU(2) and U(1) coupling constants g_2 and g_1, the top Yukawa coupling constant has a quasi-IR fixed point given by $g_T(M_Z) = \frac{\sqrt{8}}{3} g_3(M_Z)$. This yields a top mass of roughly 197 GeV. More accurately, the renormalization group equations can be numerically integrated to find the top quark mass $m_T = \frac{1}{\sqrt{2}} g_T(m_T) v'$ for a given compositeness scale Λ. In performing this integration, however, we must incorporate the fact that the SUSY partners have masses of order the SUSY breaking scale Δ. Thus for scales $\lesssim \Delta$ these degrees of freedom cease to contribute. A rough accounting for this is achieved by allowing Δ to vary such that for scales greater than Δ we employ the SUSY standard model renormalization group equations (22), while for scales less than Δ we use the ordinary standard model renormalization group equations given by [2]

$$16\pi^2 \frac{d}{dt} g_T = g_T \left(\frac{9}{2} g_T^2 - 8 g_3^2 - \frac{9}{4} g_2^2 - \frac{17}{12} g_1^2 \right)$$

$$16\pi^2 \frac{d}{dt} g_3 = -7 g_3^3$$

$$16\pi^2 \frac{d}{dt} g_2 = -\frac{19}{6} g_2^3$$

$$16\pi^2 \frac{d}{dt} g_1 = \frac{41}{6} g_1^3. \tag{23}$$

The resulting top quark mass is displayed in Table 1 as a function of both Λ and Δ.

$\Lambda\backslash\Delta$	10^2	10^3	10^4	10^5	10^6	10^8	10^{10}
10^4	330	365					
10^5	285	308	326				
10^6	259	276	290	302			
10^7	242	256	268	277	285		
10^8	231	242	252	260	267		
10^9	222	232	241	248	254	263	
10^{10}	215	224	232	238	244	253	
10^{11}	210	218	225	231	236	244	250
10^{12}	206	213	220	225	230	237	242
10^{13}	203	209	215	220	224	231	236
10^{14}	200	206	211	216	220	226	231
10^{15}	198	203	208	212	216	222	227
10^{16}	196	201	205	209	213	219	223
10^{17}	194	199	203	207	210	215	220
10^{18}	193	197	201	205	208	213	217
10^{19}	191	196	200	203	206	211	214

Table 1. The Top Quark Mass As A Function Of The Compositeness Scale Λ And The SUSY Breaking Scale Δ (All Values Are In GeV)

In conclusion, we have studied the possibility of implementing the electroweak symmetry breaking in the SUSY standard model via a dynamical top quark multiplet condensation mechanism in which the Higgs multiplets are composites. We find phenomenologically acceptable values for the top quark mass corresponding to SUSY breaking scales of the order of the electroweak scale and a range of compositeness scales. For example, with a SUSY breaking scale of 10^3 GeV and a compositeness scale of 10^{15} GeV, the top quark mass is 203 GeV.

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Figure Captions

Figure 1: Schwinger-Dyson equation for the dynamically generated top quark mass.

Figure 2: Induced kinetic term for the H' multiplet.

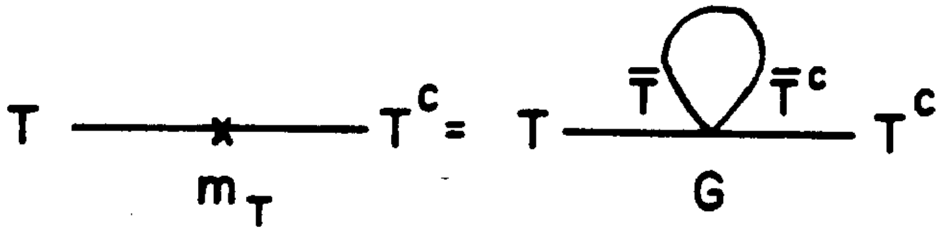

Figure 1

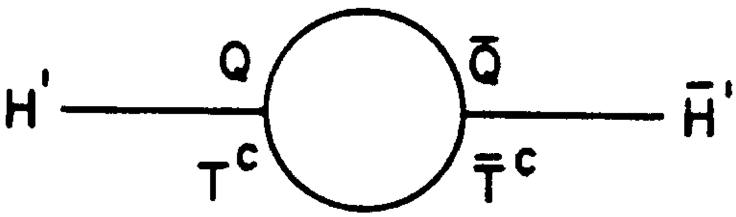

Figure 2