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ASPECTS OF UNIFIED GAUGE THEORIES *)

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A B S T R A C T

The talk is divided into two parts. The first part outlines the phenomenology of an $SO(10)$ model which breaks down to $SU(3)_c \times U(1)_{em}$ via $SU(4)_c \times SU(2)_L \times SU(2)_R$. The second part describes how a strong first order phase transition in unified gauge theories may suppress the superheavy magnetic monopole density at the time of nucleosynthesis.

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1. - MOTIVATION FOR GOING BEYOND MINIMAL SU(5)

Let us list some reasons which motivate us to go beyond SU(5) ¹ in search of a unified gauge model of strong, weak and electromagnetic interactions.

- a) Fermions of each generation belong to a reducible representation, i.e., to $\bar{5}_L + 10_L$ of SU(5).
- b) Since the maximal electroweak subgroup of SU(5) is $SU(2)_L \times U(1)$, the observed parity violation in weak interactions is put in by hand.
- c) Mass relations exist in SU(5) that involve charge $-\frac{1}{3}$ quarks and charged leptons. However, nothing can be said about charge $\frac{2}{3}$ quarks.
- d) SU(5) predicts $(m_d/m_s) = (m_e/m_\mu)$ in the asymptotic limit ². This is known to be badly violated.
- e) Although B+L is violated, B-L remains as an accidental global symmetry of SU(5). The apparent masslessness of the neutrino is accidental in SU(5) which is not very satisfactory.
- f) The baryon asymmetry in the Universe as predicted by minimal SU(5) is several orders of magnitude too small.
- g) Last, but by no means least, the experimental value of $\sin^2 \theta_W$ may be somewhat larger than the SU(5) prediction ³ of 0.2.

A MINIMAL SO(10) MODEL

The fermions of each generation belong to the 16 dimensional irreducible spinor representation of SO(10) ⁴. The maximal electroweak subgroup is $SU(2)_L \times SU(2)_R \times U(1)$ ⁵ which is left-right symmetric and is superstrongly broken down to $SU(2)_L \times U(1)$. Points (a) and (b)

listed above are therefore easily taken care of. The resolution of the remaining points requires a more detailed analysis ⁶ which we briefly describe. One is led to what one may call a minimal SO(10) model.

SYMMETRY BREAKING PATTERNS IN SO(10)

By employing a minimal Higgs system ($\underline{45}$, $\underline{126}$ and $\underline{10}$ or $\underline{54}$, $\underline{126}$ and $\underline{10}$) the following symmetry breaking patterns are allowed :

- i) $SO(10) \rightarrow SU(3)_c \times SU(2)_L \times U(1) \rightarrow SU(3)_c \times U(1)_{em}$
- ii) $SO(10) \rightarrow SU(5) \rightarrow SU(3)_c \times SU(2)_L \times U(1) \rightarrow SU(3)_c \times U(1)_{em}$
- iii) $SO(10) \rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R \rightarrow SU(3)_c \times SU(2)_L \times U(1) \xrightarrow{\downarrow} SU(3)_c \times U(1)_{em}$

Scheme iii) :

Predicts $\sin^2 \theta_W > 0.2$ (see (g)),

Keeps the "good" SU(5) predictions,

Overcomes (c), (d), (e) and (f),

Predicts the top quark mass plus the masses of the particles of a possible fourth generation,

Is likely to avoid the cosmological monopole problem since it necessarily involves a strong first order phase transition ⁷.

PROTON LIFETIME

Consider the breaking

$$SO(10) \xrightarrow[M_X]{54} SU(4)_c \times SU(2)_L \times SU(2)_R \xrightarrow[M_R]{126} SU(3)_c \times SU(2)_L \times U(1) \xrightarrow{10 \downarrow M_L} SU(3)_c \times U(1)_{em}$$

Using standard renormalization group arguments ⁸

$$M_X \sim 10^{15} \text{ GeV}$$

$$M_R \sim (1-2) \times 10^{13} \text{ GeV}$$

$$\text{with } \sin^2 \theta_W \simeq 0.23 \text{ and } \alpha_s(M_L) \simeq 0.11$$

The proton lifetime τ_p is estimated to be ⁹

$$\tau_p \simeq (1-20) \times 10^{31} \text{ yr.}$$

Note that B-L violating processes in SO(10) are strongly suppressed. It would be difficult to distinguish between SU(5) and this SO(10) model on the basis of proton decay ¹⁰.

CHARGED FERMION MASSES

The main breaking of SU(2)_L × U(1) down to U(1)_{em} is achieved by the SU(2)_L doublets contained in $\underline{10}$. However, due to mixing, the SU(2)_L doublets in $\underline{126}$ acquire an induced vacuum expectation value v where ⁶

$$v \simeq (M_R/M_X)^2 \langle \underline{10} \rangle \ll \langle \underline{10} \rangle$$

This has the following effect on the fermion mass relations obtained by considering only the $\underline{10}$.

- i) The bad relation $m_d = m_e$ involving the first generation is substantially altered. Indeed, in contrast to minimal SU(5), there is enough freedom in this minimal SO(10) model to arrange matters so that the first generation masses and the Cabibbo angle come out right.
- ii) The mass relations involving the second generation are altered by about 10%. i) and ii), when taken together, take care of (d).
- iii) Mass relations involving the third and possible fourth generation are essentially unchanged.

Examples

$$m_b(M_R) = m_\tau(M_R) \pm 1\%$$

$$\rightarrow m_b(10 \text{ GeV}) \simeq 4.6 - 5.5 \text{ GeV}$$

$$m_s(M_R) = m_\mu(M_R) \pm 10\%$$

$$\rightarrow m_s(1 \text{ GeV}) \simeq (370-500) \text{ MeV} \pm 10\%$$

Top quark mass

$$m_t(M_R) = m_c(M_R) (m_\tau(M_R)/m_\mu(M_R)) \pm 10\%$$

$$\rightarrow m_t(40 \text{ GeV}) \simeq 20 \pm 2 \text{ GeV}$$

Fourth generation

It is possible to have a fourth generation ν_τ, τ, t', b' in the SO(10) scheme discussed here. Their masses can be predicted as follows.

One expects that

$$17 \text{ GeV} \leq m_{\tau'} \leq 20 \text{ GeV}$$

where the lower bound is experimental and the upper bound comes from the requirement¹¹ that the Yukawa couplings should not become strong anywhere in the range between M_L and M_X . We then predict

$$m_t, (2m_t) \simeq 170 - 200 \text{ GeV}$$

$$m_b, (2m_b) \simeq 38 - 45 \text{ GeV}$$

NEUTRINO MASSES¹²

The decomposition of 16 under $SU(4)_C \times SU(2)_L \times SU(2)_R$ is as follows :

$$16 \rightarrow (4, 2, 1) + (\bar{4}, 1, 2)$$

One has both left-handed (ν_L) and right-handed (ν_R) neutrino fields. Let us consider one generation. Then

ν_R acquires a Majorana mass term of order M_R (through 126)

ν_L acquires an induced Majorana mass term of order M_L^2/M_R (through 126)

One also has $m_V^{\text{Dirac}} = m_{\frac{2}{3}}$ (from 10 ; see point c) above).

The neutrino mass matrix is as follows :

$$\frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} c & b \\ b & a \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{h.c.}$$

where

$$a \sim M_R \gg b \sim m_{\frac{2}{3}} \gg c \sim (M_L^2/M_R)$$

Diagonalization leads to two Majorana mass eigenstates with eigenvalues M_R and $c - b^2/a$. The "heaviest" light neutrino mass can lie in the 1-10 eV range (point e)).

BARYON ASYMMETRY

An interesting source of generating baryon asymmetry in the Universe within the $SO(10)$ model may be the decay of superheavy right-handed neutrinos at temperatures below M_R ¹³. With suitable Yukawa couplings and the above value for the Majorana mass, it seems possible to account for a baryon asymmetry of order $10^{-8 \pm 1}$ (point f)).

2. - FIRST ORDER PHASE TRANSITION AND MAGNETIC MONOPOLE SUPPRESSION

Our reasons for supposing that a strong first order ¹⁴ phase transition can suppress the 't Hooft-Polyakov ¹⁵ density differ somewhat from the arguments given in Ref. 16. Let us briefly summarize ¹⁷ the scenario for the $SU(5)$ case ⁷ with a Higgs potential involving one 24-plet.

At very high temperatures ($T > T'_{c1} \approx 10^{16}$ GeV) the $SU(5)$ symmetry is fully operative and no monopoles are present. At a temperature $T < T'_{c1}$, the effective Higgs potential develops a local minimum corresponding to the $SU(4) \times U'(1)$ phase which, to start with, is thermodynamically unfavoured compared to the $SU(5)$ phase. However, the former phase quickly overtakes the latter in being the lower minimum and, after further cooling, the $SU(5)$ phase is not even a local minimum of the potential. The system then undergoes a rapid transition (at temperature T_{c1}) to the $SU(4) \times U'(1)$ phase. Superheavy magnetic monopoles carrying $SU(4)$ and $U'(1)$ magnetic charges are produced.

As the Universe cools further in the $SU(4) \times U'(1)$ phase, the Higgs potential develops a local minimum corresponding to the $SU(3)_c \times SU(2)_L \times U(1)$ phase which becomes degenerate with the former phase at some critical temperature T_c . After more cooling, the $SU(3)_c \times SU(2)_L \times U(1)$ phase has lower free energy than the $SU(4) \times U'(1)$ phase. For reasonable choice of Higgs parameters a large barrier separates the two minima. The transition from the false to the true vacuum proceeds through barrier penetration (bubble formation) which, at least to start with, is a rather slow process. Therefore, the Universe will supercool in the false ($SU(4) \times U'(1)$) phase until a temperature T_{c2} is reached at which the rate of barrier penetration becomes large. Indeed, at temperature T_{c2} , the false phase in our case becomes a local maximum in its $SU(4)$ directions. As soon as this happens, the false vacuum decays almost instantaneously into the true vacuum. Some comments are in order :

- 1) If the Universe stays in the false ($SU(4) \times U'(1)$) phase for a sufficiently long time, it undergoes an exponential expansion until the temperature T_{c2} is reached. The formation of bubbles of the true ($SU(3)_c \times SU(2)_L \times U(1)$) vacuum in the early stages of the phase transition can be neglected since they can, at most, only expand with the speed of light.
- 2) The probability of converting the false ($SU(4) \times U'(1)$) monopoles to $SU(3)_c \times SU(2)_L \times U(1)$ monopoles is expected to be very low. They will mostly be annihilated.
- 3) The release of latent heat at T_{c2} warms the Universe back to $T_r < T_c$. Typically, $T_r \approx 0.45 T_c$. The monopole density is expected ¹⁵ to be proportional to $\exp(-(m(T_r)/T_r))$, with $(m(T_r)/T_r) \approx 70-80$. Thus, as desired, monopole production is strongly suppressed by a first order transition.

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FIGURE CAPTION

Plot of SU(5) phase diagram with one 24 plet ϕ of Higgs fields.
 The Higgs potential is

$$V = \frac{a}{4}(\text{Tr}\phi^2)^2 + \frac{b}{2}\text{Tr}\phi^4 + \frac{c}{3}\text{Tr}\phi^3 - \frac{\mu^2}{2}\text{Tr}\phi^2.$$

Define $\eta = a/b > -\frac{7}{15}$ and $\xi = -\mu^2 b/c^2$ ($b > 0$). To the right of A only the SU(5) phase exists. Between A and A' a local minimum corresponding to SU(4) $\times$ U'(1) appears. To the left of A' the SU(4) $\times$ U'(1) phase is the absolute minimum and becomes the sole minimum between $\xi = 0$ (where SU(5) disappears) and B. To the left of B there appears a local minimum corresponding to SU(3)_C $\times$ SU(2)_L $\times$ U(1). Between C and D the SU(4) $\times$ U'(1) phase is the false minimum. To the left of D the SU(4) directions develop instabilities. The false vacuum then decays instantaneously to the true SU(3)_C $\times$ SU(2)_L $\times$ U(1) vacuum.

SU(5) PHASE DIAGRAM