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UNITY OF FORCES AND THE ORIGIN OF FAMILIES AND MASS SCALES*

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I. Preliminary Remarks

The concept of grand unification comprising unification of basic matter and of its forces is now two-decades old[1-4]. One of the hall marks of this idea is proton decay. As we know, owing to the dedicated proton-decay searches[5] especially at the IMB detector in the U.S. and the Kamiokande detector here in Japan, and most recently the precision measurements of the standard model coupling constants at LEP[6], the minimal non-supersymmetric $SU(5)$ model of grand unification[2] is now excluded. But the idea of the union of the coupling constants can well materialize in accord with the LEP data and the proton-decay searches by either invoking supersymmetry[7, 8], and/or assuming a two-step breaking of a bigger symmetry like $SO(10)$[9, 10].

Such extensions of minimal $SU(5)$ were proposed on aesthetic grounds long before the dedicated proton-decay searches began. These yield (or can yield) longer lifetimes for proton-decay, typically in the range of 10^{31}-10^{35} years, as well as higher $\sin^2\theta_W$ compared to those predicted by the minimal $SU(5)$-model[4], both in accord with the data. The SUSY-extensions typically lead to prominent strange-particle decay modes, e.g. $p \to \overline{\nu}K^+$ and $n \to \overline{\nu}K^0$, while a two step breaking of $SO(10)$ can lead to prominent $\Delta(B-L) = -2$ decay modes by Higgs-exchange such as $p \to e^-\pi^+\pi^+$ and $n \to e^-\pi^+$[11] and even $n \to e^-e^+\nu_e$ etc.[12], in addition to or superceding the canonical $p \to e^+\pi^0$-mode. It is encouraging that such lifetimes and the non-canonical decay modes can be probed at least to a large extent at the forthcoming Super Kamiokande detector.

This morning, I had the pleasure of seeing the initial phase of the hole dug for installing the Super Kamiokande. It is indeed a great tribute to Japan and the Japanese physicists. It provides a *big ray of hope* that (a) one will be able to probe much deeper into neutrino-physics in the near future and (b) proton-decay may even be discovered within the twentieth century, following the completion of this detector. Undoubtedly Super Kamiokande, together with the existing detectors such as SAGE and GALLEX and the forthcoming SNO and BOREXINO and others will help open a new chapter in particle physics.

With these preliminary remarks, I turn to the main topic of my talk in which I wish to present a new approach to grand unification. It is an attempt to remove much of the arbitrariness associated with the conventional approach to grand unification as regards the choice of parameters, while preserving the essential concept of unification of matter and of its forces.

II. Unity With Quarks or Preons?

Grand unification appears to be an attractive concept because it is the only known quantum field theoretical framework that we have which explains (i) the quantization of electric charge, (ii) the existence of quarks and leptons with $Q(e^-) = -Q(p)$ and (iii) the existence of the strong, the electromagnetic and the weak forces with $g_3 \gg g_2 \gg g_1$ at low energies but $g_3 = g_2 = g_1$ at high energies. It also provides a compelling reason for non-conservation of B and/or L, which may well be necessary to explain baryogenesis despite electroweak $B+L$ violation. Furthermore, it implies the existence of short-distance physics at scales that are intermediate between the Planck and the electroweak scales. Such physics may well be necessary to understand (a) the tiny masses of the neutrinos (if the solar-neutrino deficit is real), and very likely also (b) inflation and (c) the origin of cold dark matter. For these reasons, I believe that grand unification *as a concept* may well be a step in the right direction. It is likely to be contained either explicitly or implicitly (as discussed below) within a more fundamental theory.

In the context of such a concept, it is commonly believed that the unity of the electroweak and the QCD forces occurs at an ultrahigh momentum scale $\geq 10^{14}$ GeV at which quarks and leptons exhibit their unity as well. This in essence presumes, of course, that quarks, leptons are somehow elementary. We will refer to this as the "*conventional approach*" to grand unification.

As mentioned above, the meeting of the three coupling constants g_3, g_2 and g_1 can well materialize within this conventional approach in accord with the LEP data by either invoking supersymmetry[7, 8] into e.g. minimal $SU(5)$ (or $SO(10)$) and/or assuming a two-step breaking of a bigger symmetry like $SO(10)$[9, 10]. Despite this success as regards the meeting of the coupling constants, it seems to me that neither of the two schemes is likely to constitute a fundamental theory *by itself*, because each scheme possesses *a large number of widely varying arbitrary parameters* (typically some two dozens) associated with the quartic and the Yukawa couplings and the masses of the Higgs bosons. And neither of them explains the three major puzzles:

1. the origin of the three chiral families
2. the origin of the inter-family mass-hierarchy and
3. the origin of the diverse mass-scales – from M_{Planck} to m_ν – and thereby of the associated small numbers such as $(m_W/M_{p\ell}) \approx 10^{-17}, (m_e/M_{p\ell}) \approx 10^{-22}$ and $(m_\nu/m_{P\ell}) < 10^{-27}$.

One might hope that one of the two schemes – i.e. the minimal $SUSYSU(5)$ or the $SO(10)$-model with the desired spectrum – emerges from one of the

superstring theories[13, 14], which could account for the parameters in just the right way and thereby remove the arbitrariness. This would, of course, be the best of all worlds. But so far, the superstring theories are rather far from soing so.

First of all, there is a plethora of classically allowed solutions for the four-dimensional ground state or the vacuum of superstring theories corresponding to the Calabi-Yau, orbifold and four-dimensional constructions and one is not yet in a position to (a) choose between them, (b) understand the breaking of supersymmetry and (c) generate a mass for the dilaton. Notwithstanding these fundamental difficulties, which would need a handling of the non-perturbative string dynamics, *there does not seem to be even a single solution among the vast set of solutions (mentioned above) which resembles or nearly resembles the known world.* In particular, there is not even a vague indication so far of a minimal $SUSYSU(5)$ or $SO(10)$-model with the desired spectrum emerging from a superstring theory[15]. If this persists, believing that the "final picture" should not only exhibit a meeting of the coupling constants but also should (a) explain the three puzzles and (b) remove the arbitrariness in the choice of parameters mentioned above, it seems to me that the union of the coupling constants in the context of the minimal $SUSY$ grand unification model(s)[8] may well be fortutious. It should at least be taken with some caution because there are in fact alternative ways by which such a meeting may occur.

This brings me to consider the idea of the unity of forces within an alternative approach[16], based on a supersymmetric composite model of quarks, leptons and Higgs bosons. To begin with, the model is viable and is devoid of much of the arbitrariness mentioned above. It is manifestly economical in its field content and especially in its parameters, which correspond to just a few gauge couplings (see below) but it has no mass, quartic and Yukawa couplings. This is the main advantage of the composite picture. [If one reflects upon it, the standard Yukawa and quartic couplings of the Higgs bosons are not dictated by a principle, such as local gauage invariance. They are therefore, best generated effectively at a composite level through fundamental gauge interactions like the pion-nucleon and the pion-pion couplings in QCD.] The model, furthermore, seems capable of addressing successfuly the issues of the origins of (i) families[17], (ii) inter-family mass-hierarchy[18] and (iii) diverse mass-scales[16]. One important feature is that it provides several testable predictions by which it can be excluded, if it is wrong. And last but not least, it is recently shown that the unity of forces may well occur at the level of preons near the Planck scale[19]. For these reasons, it seems prudent to at least keep an open mind as regards whether quarks and leptons are truly elementary or composite. To present some of these results, I will first recall a few salient features of the model.

III. A Preon Model with a Unification of Scales – From M_{Pl} to m_ν

The model[16] is defined through an effective lagrangian, just below the Planck scale, processing $N = 1$ local supersymmetry and a gauge symmetry of the form $G_M \times G_{fc}$. Here the symmetry $G_M = SU(N)_M$ (or $SO(N)_M$) generates an asymptotically free metacolor gauge force which binds presons and G_{fc} denotes the flavor-color gauge symmetry, which is assumed to be either $G_0 = SU(2)_L \times SU(2)_R \times SU(4)^C$[1], or a subgroup of G_0 containing $SU(2)_L \times U(1) \times SU(3)^C$. The gauge symmetry $G_M \times G_{fc}$ operates on a set of preonic constituents consisting of six positive and six negative *massless* chiral superfields $\Phi^a_\pm = (\varphi^a_{L,R}, \psi^a_{L,R}, F^a_{L,R})$. Each of these transforms as the fundamental representation $\underline{N}$ of $G_M = SU(N)_M$. The index a runs over six values: $(x, y); (r, y, b, l)$, where (x, y) denote the two basic flavor-attributes (u, d) and (r, y, b, l) the four basic color-attributes of a quark-lepton family[1]. Thus $\Phi^{x,y}_+$ and $\Phi^{x,y}_-$ transform as doublets of $SU(2)_L$ and $SU(2)_R$ respectively, while both $\Phi^{r,y,b,l}_+$ and $\Phi^{r,y,b,l}_-$ transform as quartets of $SU(4)^C$. The effective lagrangian of this model turns out to possess only gauge and gravitational interactions. As a result, the model involves *atmost only three or four parameters* (see below) corresponding to the coupling constants of the gauge symmetry $G_M \times G_{fc}$. Even these few would merge into one near the Planck scale if there is an underlying unity of forces-in particular through superstrings (see remarks later).

Such a model has not yet been derived from a superstring theory, although there does not appear to be any bar, in principle in this regard especially in the context of four-dimensional construction[14]. Even without such a derivation, if one introduces the economical preon-picture mentioned above through an effective lagrangian just below the Planck scale and assumes $N = 1$ local supersymmetry, one seems to be able to derive a number of advantages. These include:

(i) *A Unification of Scales*: It is shown[16] that the model is capable of generating all the diverse scales – from M_{Planck} to m_ν – and thereby the small numbers such as $(m_W/M_{pl}) \sim (m_t/M_{pl}) \sim 10^{-17}, (m_C/M_{pl}) \sim 10^{-19}, (m_e/M_{pl}) \sim 10^{-22}$, and $(m_\nu/M_{pl}) < 10^{-27}$ – *in terms of just one fundamental input parameter*: the coupling constant α_M associated with the metacolor force. Corresponding to an input value $\overline{\alpha}_M \approx 1/27$ to $1/32$ at $M_{Pl}/10$, the metacolor force generated by $SU(N)_M$ becomes strong at a scale $\Lambda_M \approx 10^{11} GeV$ for N=5 to 6. Thus the first big step in the hierarchical ladder leading to the small number $(\Lambda_M/M_{Pl}) \sim 10^{-8}$ arises naturally through renormalization group equations due to the slow logarithmic growth of $\overline{\alpha}_M$ and its perturbative input value at $M_{Pl}/10$. This in turn generates the remaining steps as follows.

When the metacolor force becomes strong and confining at Λ_M, it serves many functions:

(a) It binds preons to make metacolor singlet composite quarks and leptons. It turns out (see remarks later) that at the level of minimum dimensional composite operators, the model yields three (rather than one) chiral familes $q^i_{L,R}$ and in addition *two vector-like families* $Q_{L,R}$ and $Q'_{L,R}$, which are doublets of $SU(2)_L$ and $SU(2)_R$ respectively.

(c) It is assumed that the metacolor force also makes a few *SUSY-preserving* preon-condensates which include a condensate Δ_R transforming as $(1,3,\overline{10})$ under $G_0 = SU(2)_L \times SU(2)_R \times SU(4)^C$. These condensates naturally have a scale of order Λ_M. $< \Delta_R >$ breaks G_0 into $SU(2)_L \times U(1)_Y \times SU(3)^C$ and gives a heavy Majorana mass of order $\Lambda_M \sim 10^{11} GeV$ to the composite ν_R's.

(c) The remaining small scales including SUSY-breaking mass-splittings $\delta m_S \sim 1$ TeV and $m_W \sim 100$ GeV arise[20, 16] due to the constraints of the Witten index theorem[21], which would forbid (in the class of models under consideration) a dynamical breaking of SUSY, if there was no gravity (i.e. in the limit $M_{Pl} \to \infty$).

As a result, noting that, owing to the Konishi anomaly, both the metagaugino condensate $< \vec{\lambda} \cdot \vec{\lambda} >$ and the preonic condensate $< \overline{\psi}^a \psi^a >$ break SUSY, for the case of massless preons, they must both need the collaboration between the strong metacolor force and perturbative gravity to form. Assuming that they do form, one can argue plausibly that they must each be damped by (Λ_M/M_{Pl})[20] – i.e. $< \vec{\lambda} \cdot \vec{\lambda} >= a_\lambda \Lambda_M^3 (\Lambda_M/M_{Pl})$; $< \overline{\psi}^a \psi^a >= a_{\psi_a} \Lambda_M^3 (\Lambda_M/M_{Pl})$, where a_λ and a_{ψ_a} are of order unity; a_{ψ_a} is expected to be smaller than a_λ by factors of 5-10 because ψ's are in the fundamental and λ's in the adjoint representation. Since $< \overline{\psi}^a \psi^a >$ break not only SUSY but also $SU(2)_L \times U(1)_Y$ for $a = x, y$, one obtains SUSY-breaking mass-splittings $\delta m_S \sim \Lambda_M (\Lambda_M/M_{Pl}) \sim 1$ TeV and $m_W \sim (1/10)\Lambda_M(\Lambda_M/M_{Pl}) \sim 100$ GeV, which constitute the second and the third steps in the hierarchical ladder. These too have arisen naturally, now due to the Witten index theorem. The Dirac masses of the fermions (including the neutrinos) are also damped by (Λ_M/M_{Pl}).. This leads to $m_t \sim m_W \sim 100$ GeV. As explained below, the inter-family hierarchy including $(m_e/m_t) \sim 10^{-5}$ arises naturally due to additional symmetries in the fermion mass-matrix[18].

Finally, the familiar see-saw mechanism for neutrinos with $m(\nu^i_R) \sim \Lambda_M \sim 10^{11}$ GeV and $m(\nu^i)_{Dirac} \propto \Lambda_M(\Lambda_M/M_{Pl})$ yields $m(\nu^i_L)$ $\leq 10^{-3} M_{Pl}(\Lambda_M/M_{Pl})^3 \sim 10^{-27} M_{Pl}$. In this way, the model provides, remarkably enough, a *common origin* of all the diverse scales – from M_{Pl} to m_ν[16], as desired.

(ii) *Family Replication*: One can argue plausibly that the composite operator giving massless spin-1/2 quark (or lepton) consists of a minimum of three constituents[22]. Recognizing that in a SUSY theory, fermionic constituents can be interchanged by their boson partners (i.e. $\psi \leftrightarrow \varphi$ and $v_\mu \leftrightarrow \lambda$ or $\overline{\lambda}$ etc.), there exist several alternative three-particle combinations with identical quan-

tum numbers, which can make a left-chiral $SU(2)_L$-doublet family q_L^i – e.g. (i) $\sigma_{\mu\nu}\psi_L^f\varphi_R^{c^*}v_{\mu\nu}$, (ii) $\sigma^{\mu\nu}\varphi_L^f\psi_R^{c^*}v_{\mu\nu}$, (iii) $\psi_L^f\psi_R^{c^*}\lambda$ and (iv) $\varphi_L^f(\sigma^\mu\overline{\lambda})\partial_\mu\varphi_R^{c^*}$. Here $f = x$ or y corresponds to up or down flavors and $c = (r, y, b)$ or ℓ corresponds to the four colors. ***The plurality of these combinations, which stem because of SUSY, is in essence the origin of family-replication.*** As mentioned before, by constructing composite superfields, Babu, Stremnitzer and I showed[17] that at the level of minimum dimensional composite operators (somewhat analogous to qqq for QCD) there are just three linearly independent chiral families $q_{L,R}^i$, and, in addition, two ***vector-like families*** $Q_{L,R}$ and $Q'_{L,R}$, which couple vectorially to W_L's and W_R's respectively. Each of these composite families is, of course, accompanied by its scalar superpartners. To sum up, we see that owing to fermion-boson pairing in SUSY, the model provides a compelling reason for replication and at least some rationale, subject to the assumption of saturation at the level of minimum dimensional composite operators, as to why the number of chiral families is three. Clearly this last assumption needs further justification. Pending such a justification, however, let us still proceed to examine the masses of the fermions belonging to this system of ***five families*** – three chiral and two vector-like. We will see that such a system has some unique desirable features.

(iii) *Inter-family Mass-Hierarchy:* First note that for the purposes of quantum numbers, the chiral and vector-like families can be represented by $q_L \sim$ "$\psi_L^f\varphi_R^{c^*}v$", $q_R \sim$ "$\psi_R^f\varphi_L^{c^*}v$", $Q_L \sim$ "$\psi_L^f\varphi_L^{c^*}v$", $Q_R \sim$ "$\varphi_L^f\psi_L^{c^*}v$", $Q'_L \sim$ "$\varphi_R^f\psi_R^{c^*}v$" and $Q'_R \sim$ "$\psi_R^f\varphi_R^{c^*}v$". Utilizing these compositions, one can see that the vector-families $Q_{L,R}$ and $Q'_{L,R}$ acquire relatively heavy masses through the metagaugino condensate $< \vec{\lambda}\cdot\vec{\lambda} >$ of order $a_\lambda\Lambda_M(\Lambda_M/M_{Pl}) \sim 1$ TeV, which are otherwise protected by the $U(1)_X$ quantum number of the SUSY theory. Since $< \vec{\lambda}\cdot\vec{\lambda} >$ is flavor and color-blind, however, all members of the vector families – *i.e.* U, D, E, N, as well as U', D', E' and N' – acquire the same mass, barring QCD and electroweak corrections.

The chiral families $q_{L,R}^i$ acquire masses primarily through their mixings with the vector-like families $Q_{L,R}$ and $Q'_{L,R}$ which are induced by $< \bar{\psi}^a\psi^a >$. This is because the direct mass-terms $m^{(o)}(q_L^i \to q_R^i)$ as well as the $Q - Q'$ mixing terms cannot be induced through either $< \vec{\lambda}\cdot\vec{\lambda} >$ or $< \bar{\psi}\psi >$. These receive small contributions at most of order (1/10-1) MeV from products of $< \bar{\psi}\psi >$ and $< \varphi^*\varphi >$ condensates, each of which is damped by (Λ_M/M_{Pl}). Thus, dropping these direct and $Q - Q'$ mixing mass-terms, and ignoring QCD corrections for the quarks for a moment, the Dirac-mass matrices of the five families for all

four sectors - i.e., q_u, q_d, l and ν - have the form[16, 18]:

$$M^{(o)}_{f,c} = \begin{array}{c} \\ \bar{q}^i_R \\ \bar{Q}_R \\ \bar{Q}'_R \end{array} \begin{array}{c} \begin{array}{ccc} q^i_L & Q_L & Q'_L \end{array} \\ \begin{pmatrix} O & X\kappa_f & Y\kappa_c \\ Y'^{\dagger}\kappa_c & \kappa_\lambda & O \\ X'^{\dagger}\kappa_f & O & \kappa_\lambda \end{pmatrix} \end{array} \tag{1}$$

The index i runs over three families. The entitites X, Y, X' and Y' are column matrices in the family-space having entries which are apriori of order unity. In the above, $\kappa_f \equiv \mathcal{O}(a_{\psi_f})\Lambda_M(\Lambda_M/M_{Pl}), \kappa_c \equiv \mathcal{O}(a_{\psi_c})\Lambda_M(\Lambda_M/M_{Pl})$ and $\kappa_\lambda \equiv \mathcal{O}(a_\lambda)\Lambda_M(\Lambda_M/M_{Pl})$. Following remarks made above, we expect $\kappa_\lambda \approx (3 - 10)\kappa_{f,c}$. As a result, the Dirac mass-matrices of all four sectors have *a natural see-saw structure.*

In the absence of electroweak corrections, which are typically of order 5-10%, due to left-right symmetry and flavor-color independence of the metacolor force, *not only* $X^T = (X')^T$ *and* $Y^T = (Y')^T$, *but the same* X, Y *and* κ_λ *apply to all four sectors: up, down, charged leptons and neutrinos.* Furthermore, ignoring electroweak corrections for a moment, one can always rotate the chiral quark or lepton fields q^i_R and q^i_L to bring the row matrices $Y^T = (Y')^T$ to the simple form $(0, 0, 1)$ and simultaneously $X^T = (X')^T$ to the form $(0, p, 1)$, with redefined κ_f and κ_c. Note the consequent great reduction even in effective parameters. The 5×5 mass-matrices of the four sectors – i.e. q_u, q_d, q_ℓ and ν – which, in general could involve at least 100 parameters – are described (barring electroweak corrections and direct mass-terms ≤ 1 MeV) by only six effective parameters – i.e. $p, \kappa_u, \kappa_d, \kappa_r, \kappa_\ell$ and κ_λ. Furthermore, we know the approximate values (within a factor of ten, say) of these parameters. Upon examining the relevant preon-diagrams, one can argue that the effective parameter p is less but not very much smaller than one. A value of $p \simeq 1/3$ to $1/4$ is found to be quite natural.

Given the zeros in (1), which stem from the symmetry of the underlying SUSY preon theory, we see that regardless of the values of the entries in X and Y and thus of p, one of the five families is guaranteed to be massless, barring corrections of order 1 MeV, which thus can be identified with the electron-family[18]. In other words, inspite of the fact that all three chiral families are on par as regards their preon-content and binding, *the symmetry of the underlying SUSY-theory on the one hand and that of the system consisting of three chiral and two vector-like families on the other hand guarantee one linear combination to remain massless (up to corrections of order 1 MeV).* We find this feature most satisfying.

Furthermore, the $\mu - \tau$ mass-ratios are given by $[m_{c,s,\mu}/m_{t,b,\tau}] \approx p^2/4$. For $p \simeq 1/3$ to $1/4$, which is not too small and natural, one thus obtains a rather large $\mu - \tau$-hierarchy of $1/36$ to $1/64$, as observed. In this way, one understands

naturally why $m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\tau}$ with $m_e \sim \mathcal{O}$ (1 MeV) and $m_t \sim$ 100 GeV. Including direct mass terms in the top-left 3×3 block which are of order 1 MeV and electroweak corrections, one also obtains hierarchical CKM mixings[18].

In other words, the preon model provides at least a qualitative understanding of the bulk of the parameters associated with the standard model. In particular, it explains why $m_e/m_t \sim 10^{-5}$.

(iv) *CP Violation:* The model provides an elegant mechanism for spontaneous CP violation, which is shown to vanish (for the observed processes), if the masses of the electron family were set to zero[18]. The model predicts an electric dipole moment for the neutron $\approx$ (1 to $\frac{1}{20}$) $\times 10^{-25} ecm$, which is observable.

(v) *Crucial Tests:* One distinguishing feature of the preon model is that it leads to several crucial predictions[18] by which it can really be falsified if it is wrong. First, owing to the mixing of the chiral with the vector-like families, there are new contributions to $K^o - \overline{K}^o, K_L \to \mu^+\mu^-$ and $K_L \to \bar{\mu}e$, which are, however, smaller typically by one to two orders of magnitude than that of the standard model, while those for $B^o - \overline{B}^o$ are comparable to that of the standard model. In other words, the model is safe so far, unlike technicolor. It predicts intriguing new processes such as: (a) $Z \to t\bar{c}$ with an amplitude of order (2 to $\frac{1}{2}$)% of the normal Z^o-coupling, (b) $Z \to c\bar{u}$ which gives $\Delta m(D - \overline{D}) \approx (10 to 3) \times 10^{-14}$ GeV, which is at least 20 times bigger than that of the standard model, (c) $Z \to \bar{\mu}e$ leading to $B(\mu \to 3e) \approx (1 to 5) \times 10^{-13}$, (d) enhanced and observable $\nu_\mu - \nu_\tau$ oscillations[23] and (e) a (1 to 10)% *increase* in top and tau life-times compared to those expected in the standard model together with a predictable *decrease* in LEP neutrino counting from 3[18, 24].

One dramatic prediction and hallmark of the model is, of course, the existence of two vector-like families Q and Q' whose leptons (E, E', N, N') have masses in the range of (200-600) GeV and quarks (U, D, U', D') have masses $\approx (600 - 2000)$ GeV[16, 18]. They are not only predicted by the model; but, as discussed before, *they also serve a very useful purpose in providing a natural see-saw pattern for the quark-lepton masses and, thereby, a qualitative understanding of the inter-family mass-hierarchy.* Furthermore, the existence of such heavy *vector-like* (rather than chiral) families is found to be perfectly compatible[24] with precision electroweak tests including measurements of the ρ and the S or ϵ_3 paramters[25]. For these reasons, I believe that it is a good bet that precisely two vector-like families await discovery at SSC and very likely, at least the leptonic members, also at LHC and TeV-range e^-e^+ colliders.

(vi) *Supersymmetry Breaking:* The preonic theory requires the presence of a new metacolor force in the *observable sector* which becomes strong at a superheavy scale $\Lambda_M >> 1$ TeV. Such a force would not, however, be permissible if quarks and leptons were elementary. The existence of such a force, in the

presence of gravity, allows the possibility of a dynamical breaking of supersymmetry directly in the observable sector (albeit with a damping by the Planck mass[20]), which thus transmits efficiently into the masses of the squarks, the gluinos and the winos. This may well be an advantage over a dynamical breaking of supersymmetry occurring entirely in the hidden sector of a superstring theory, which seems to be the only possibility in such a theory if quarks and leptons are elementary.

Given the advantages (i)-(vi) mentioned above, let us next examine the feasibility of grand unification at the preon level.

IV. Grand Unification at the Preon Level

As stated before, the preon model is defined through an effective lagrangian, just below the Planck scale, possessing $N = 1$ local supersymmetry and a gauge symmetry of the form $G_p = G_M \times G_{fc}$. Here $G_M = SU(N)_M$ (or $SO(N)_M$) and $G_{fc} = G_0 = SU(2)_L \times SU(2)_R \times SU(4)^c$ (for other possibilities, see below). Such a model already possesses at least three of the main ingredients of grand unification – i.e. (a) quark-lepton unification because of $SU(4)^{color}$, (b) quantization of electric charge because of the non-abelian nature of the gauge symmetry G_P and (c) spontaneous violation of $B - L$ because of the gauging of $B - L$. Note also that the preon-content and the gauge symmetry G_P respect left-right-symmetry. At the composite level, therefore, ν_L is accompanied by ν_R. Furthermore, subject to the assumption that the preonic condensate $< \Delta_R > \sim \Lambda_M \sim 10^{11}$ GeV forms, the physics of the preonic theory at the intermediate scale Λ_M has many features in common with that of a two-step breaking of a left-right symmetric grand unified theory like $SO(10)$ with elementary quarks and leptons and elementary Higgs Δ_R. This includes the see-saw generated light ν_L's and heavy Majorana ν_R's. In fact $< \Delta_R >$ breaks $B - L$.

What about the remaining aspect of grand unification – *i.e.* the unity of forces? The gauge symmetry G_P, subject to $L - R$ symmetry, would seem to allow three gauge coupling constants g_M, g_2 and g_4. However, if G_P and the associated preon-content (specified above) arise from an underlying superstring theory, in particular, through a four-dimensional construction[14] with $k = 1$ Kac-Moody algebra, these coupling constants would in fact be equal to each other at the string unification scale $M_{SU} \approx 10^{18}$ GeV. In this case, the spirit of grand unification would be fully retained at the level of preons.

Although the derivation of a preon model resembling that proposed in Ref. 16 from a superstring theory is still awaited, it is intriguing to ask whether the coupling constants g_1, g_2 and g_3 extrapolated in the context of the preon model from their measured values at low energies do indeed meet with each other as well as with g_M near the Planck scale, for any reasonable choice of the

metacolor gauge symmetry G_M and the flavor-color gauge symmetry G_{fc}. Note that the extrapolation involves three regions of particle-spectrum: (I) from 1 GeV to about 1 TeV where one has the standard three families of quarks and leptons and the standard gauge bosons, (II) from about 1 TeV to the metacolor scale $\Lambda_M \sim 10^{11}$ GeV where the spectrum consists of the three chiral and two vector-like quark-lepton families, the standard model gauge bosons and the superpartners of all these and (III) from $\Lambda_M \sim 10^{11}$ GeV to the unification-scale $M_{SU} \approx 10^{18}$ GeV. In region (III), the spectrum is supersymmetric as in region II and is made of preons (specified above) and the gauge particles of the metacolor gauge symmetry G_M as well as of the effective flavor-color gauge symmetry G_{fc}, which may be chosen to be either $G_0 = SU(2)_L \times SU(2)_R \times SU(4)^C$ or in general even a subgroup of G_0 containing $SU(2)_L \times U(1) \times SU(3)^C$. The precise nature of G_M and G_{fc} as well as the preon-content may hopefully get determined ultimately by an underlying superstring theory if preons have their origin from such a theory. In this case, despite the non-unifying appearance of the effective symmetry $G_M \times G_{fc}$, the constraints of grand unification including the quantization of electric charge and the familiar equality of the coupling constants near the unification scale M_{SU} would still hold, especially for $k = 1$ Kac-Moody algebra, barring, of course, Planck-scale threshold effects.

Note that the extrapolation based on renormalization group equations is fully determined in regions I and II because the spectrum and the gauge symmetry are fixed, while in region III, there is only a few discrete choices which can be made as regards the metacolor gauge symmetry G_M and the flavor-color gauge symmetry G_{fc}. The scale Λ_M is fixed at about 10^{11} GeV (within a factor of 3, say) by requiring consistency with the hierarchy of scales. In a recent work, Babu and I found[19] that with the measured low-energy values of g_1, g_2 and g_3 and thus with $\sin^2\theta_W \simeq .2333, \alpha = 1/127.9$ and $\alpha_3 = .118$ at m_Z as input, the coupling constants including g_M, remarkably enough, show a clear tendency to converge to a common value within a few percent of each other[26] at a scale $M_U \approx (2-5) \times 10^{18}$ GeV, for the choice $G_M = SU(5)_M$ and $G_{fc} = SU(2)_L \times U(1)_{I3R} \times SU(4)^C$[27]. A sketch of the running of the coupling constants $\alpha_1, \alpha_2, \alpha_3$ and α_M for this particular choice of G_M and G_{fc} is shown in Fig. 1. Note that α_2 and α_3 (just barely) loose asymptotic freedom in region II owing to contributions from composite SUSY partners. Yet, all the coupling constants including α_1, α_2 and α_3 remain perturbative[28] in the entire range of extrapolation except of course α_M which becomes strong just around Λ_M. Such a meeting of the coupling constants at the preonic level near the Planck scale, despite the few discrete choices available for G_M and G_{fc}, appears non-trivial, especially considering that α_2 and α_3 loose asymptotic freedom in region II. It demonstrates that the unity of forces may well occur at the level of preons in a manner that is truly novel compared to the conventional approach

of elementary quarks and leptons.

V. Concluding Remarks

Let us now compare the two alternative approaches to unification: One based on the idea of elementary quarks and leptons and the other on the idea of preons.

On the negative side, the preon picture possesses a certain arbitrariness with regard to the choice in the pattern of symmetry breaking and correspondingly in the precise set of condensates which form near Λ_M. While this type of arbitrariness is present in one form or another in alternative approaches as well (compare e.g. with the needed VEVs of the scalar partners of ν_R and N in the three-generation Calabi-Yau models[15]), it is clearly desirable to understand the dynamics of locally supersymmetric gauge theories to shed some light on these issues. Of special interest is the question whether vectorial global symmetries such as isospin can break dynamically in a SUSY QCD-type theory to which the premises of the Vafa-Witten theorem do not apply. Such a breaking has been presumed within the preonic approach[16]. If it can be derived on dynamical grounds, one would have a compelling reason for the breakdowsn of isospin and perhaps other global symmetries in SUSY QCD-type theories. It also remains to be seen whether the preon-content and the gauge symmetry of the type suggested in Ref. 16 can be derived from an underlying superstring theory. These are some of the challenges confronting the preon picture.

On the positive side, while the pattern of the condensates needs to be assumed within the preonic approach, the scales of the condensates including those with a damping by (Λ_M/M_{Pl}) are deduced (not assumed) on general grounds. Furthermore, even without being derived from a superstring theory as yet, the preonic approach has emerged with many attractive features:

(a) It is already most economical in parameters and building blocks and thus is devoid of much of the arbitrariness that goes with the conventional approach to grand unification involving elementary quarks, leptons and Higgs bosons.

(b) It is viable at present with regard to all available experimental probes including flavor-changing neutral current-processes and precision measurements of the electroweak parameters, unlike standard technicolor.

(c) One major advantage of the preonic approach is that it seems capable of addressing successfully the three basic issues pertaining to the origins of (1) the diverse mass-scales from M_{Pl} to m_ν, (2) family replication and (3) inter-family mass-hierarchy. Once again, none of these issues can be addressed within the conventional approach to grand unification with elementary quarks, leptons and Higgs bosons, with or without supersymmetry. And, as I mentioned before the hope of addressing these issues by deriving a conventional supersymmetric grand

unification model from a superstring theory seems to be marred because the existing vast set of solutions including Calabi-Yau, Orbifold and four-dimensional constructions do not show any promise in this regard.

(d) Last but not least, the recent work of Ref. 19 opens up the possibility that the unity of forces can occur near the Planck scale through preons rather than quarks and leptons, in accord with the recent LEP data. Thus the preonic approach seems capable of achieving the aspired *two-sided goal.* That is unification of forces and simulatneously a resolution of the issues of the origin of families and of diverse mass scales[16-18].

(e) Finally, the *real advantage* of the preonic approach, it seems to me, is that while it is capable of addressing some very basic issues, it also offers several crucial tests listed above, by which it can be excluded, if it is wrong. This is so, inspite of the fact that the compositeness scale Λ_M is found to be very high, of order 10^{11} GeV. Thus, according to this picture, on the one hand, quarks, leptons and Higgs bosons would appear point-like at energies $\ll 10^{11}$ GeV – viz. *one would not expect to see any direct sign of their compositeness through departures from point-like behavior – i.e. appearance of form factors – even at SSC energies.* Yet, on the other hand, there are several crucial though indirect low-energy tests of the idea of compositeness, developed in Ref. 16-18, on the basis of which the idea can live or die. These include a host of flavor-changing neutral-current processes, in particular $D - \overline{D}$ mixing[18] and $\nu_\mu - \nu_\tau$ -oscillations[23] on the one hand and *the unavoidable existence of two complete vector-like families*, which can be explored at SSC and possibly also LHC energies, on the other hand.

Thus, in my opinion, the preonic approach to unification, though unconventional, seems to offer *distinct advantages* over the conventional approach of elementary quarks, leptons and Higgs bosons. As such it deserves further theoretical study in all its aspects involving dynamics of locally supersymmetric QCD-type theories on the one hand and a derivation of a preon-model of the type proposed in Ref. 16 from a superstring theory on the other hand.

As a concluding remark, it may be appropriate to recall, particularly here in Japan, a historical incident.

The idea of $SU(3)$-flavor as an approximate symmetry, suggested by the Japanese physicists, turned out to be correct, but the identification of the fundamental triplet with the observed (p, n, and Λ) rather than with their constituents – i.e. the quarks – turned out to be wrong. One wonders whether a similar mistake is being repeated now by adhering to the common notion that the unity of forces should occur at the level of the observed quarks and leptons. The idea of the superstring theories and, therefore, of the unity of forces at a fundamental level may well be right. But it remains to be seen, and here experiments of the type mentioned above can help, whether the fundamental fields

emerging from such a theory correspond to the observed quarks and leptons or possibly to a new layer of constituents – the preons.

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[27] Other choices for G_M and G_{fc}, including threshold effects at Λ_M and at 1 TeV, will be considered in a subsequent paper with M. Parida.

[28] It is intriguing to note that α_1, α_2 and α_3 remain perturbative only for the minimal choice of the preon-content, which introduces just 2 flavors and 4 colors[16]. For instance, if we increase the number of preon flavors from the minimal number two to four (say), the number of chiral families must be *even* and thus at least four, so as to include the three observed families. The number of $SU(2)_L$ and likewise $SU(2)_R$–doublet vector families must also be even, and, therefore, there must be at least two of each with a mass ≈ 1 TeV. Thus there must be at least $4 + 2 + 2 = 8$ families and their superpartners contributing to the RGE in region II. In this case, given α_3 at low energies, QCD would become confining at about 10^7 GeV. Hence the increase from two to four in the number of flavors is simply not permitted. In other words, the preon content of Ref. 16 is not only the minimal choice, but also the maximal allowed one, and in fact the only possibility.

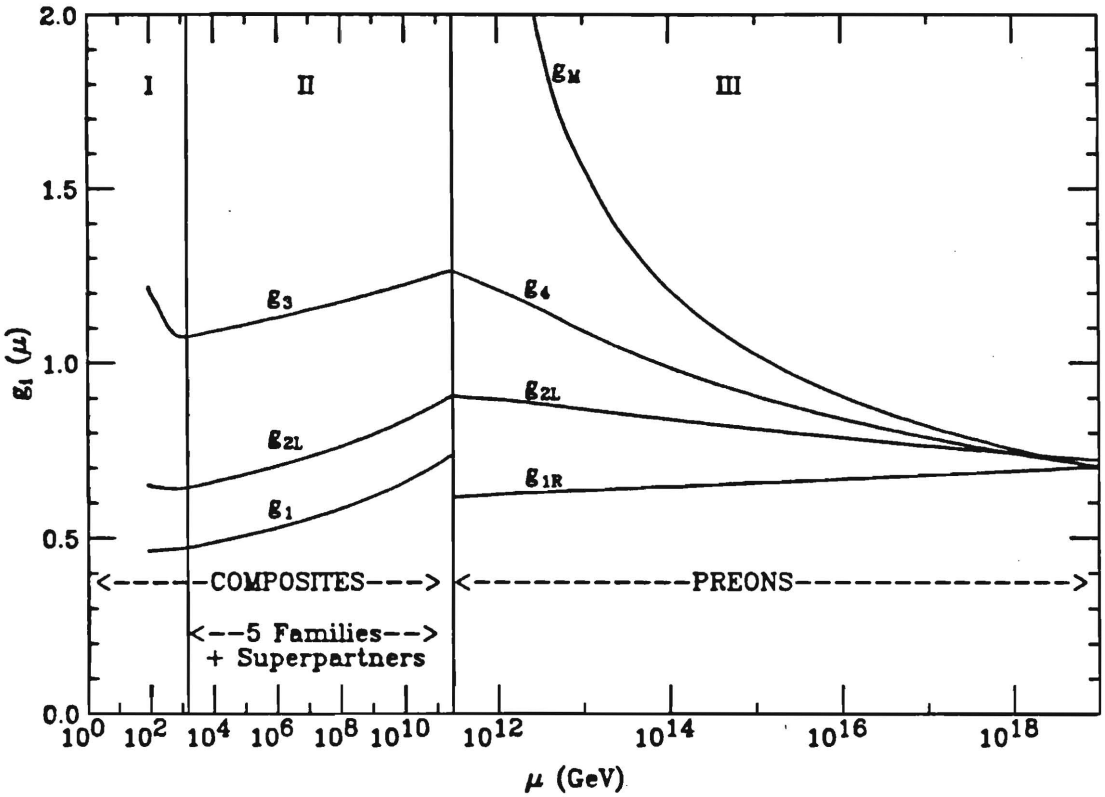

Figure 1: Running of the coupling constants in the Preon Model for the case $G_{fc} = SU(2)_L \times U(1)_R \times SU(4)^C$ with $G_M = SU(5), \Lambda_M = 3 \times 10^{11}$ GeV and the input values of g_i's at m_z given by LEP data (see text). Region I gets contributions from the standard three families and gauge bosons, while region II gets contributions from 3 chiral and two-vector like families, the Higgs-like multiplets of $< \overline{\psi}\psi >$ composites, the gauge bosons and superpartners of all these. Region III gets contributions from preons, the relevant gauge bosons and their superpartners. Details may be found in Ref. 19.