WITH NEUTRINO MASSES REVEALED, PROTON DECAY IS THE MISSING LINK

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ABSTRACT

By way of paying tribute to Abdus Salam, I recall the ideas of higher unification that he and I initiated. I discuss the current status of those ideas in the light of recent developments, including those of: (a) gauge coupling unification, (b) discovery of neutrino-oscillation at SuperKamiokande, and (c) ongoing searches for proton decay. It is remarked that the mass of $\nu_\tau$ ($\sim 1/20$ eV) suggested by the SuperK result seems to provide clear support for an underlying unity of forces based on the ideas of (i) SU(4)-color, (ii) left-right symmetry and (iii) supersymmetry. The change in perspective, pertaining to both gauge coupling unification and proton decay, brought forth by supersymmetry and superstrings is presented. The beneficial roles of string- symmetries in addressing certain naturalness problems of supersymmetry, including that of rapid proton decay, are noted. In the last section, attention is drawn to the recent joint works with K. Babu and F. Wilczek, where the influence of neutrino masses and thus of the new SuperK result on proton decay are noted. In this context, it is remarked that with neutrino masses and coupling unification revealed, the discovery of proton decay, that remains as the missing link, should not be far behind.

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\[1\]Based in part on a talk delivered at the Abdus Salam Memorial Meeting, ICTP, Trieste, November 1997.
I. Salam in Perspective

Abdus Salam was a great scientist and a humanitarian. His death was indeed a loss to science and especially to the growth of science in the third world. He will surely be remembered for his contributions to physics, some of which have proven to be of lasting value. These include his pioneering work on electroweak unification for which he shared the Nobel Prize in physics in 1979 with Sheldon Glashow and Steven Weinberg. Contribution of this calibre is rare.

But I believe his most valuable contribution to science and humanity, one that is perhaps unparalleled in the world, is the sacrifice he has made of his time, energy and personal comfort in promoting the cause of science in different corners of the globe, in particular the third world. His lifelong efforts in this direction have led to the creation of some outstanding research centres, including especially the International Centre for Theoretical Physics (ICTP) at Trieste, Italy, an International Centre for Genetic Engineering and Biotechnology with components in Trieste and Delhi, and an International Centre for Science and High Technology in Trieste. Salam dreamed of creating twenty international centres like the ICTP, spread throughout the world, emphasizing different areas of science and technology. Approaching developed as well as developing nations, for funding of such institutions, Salam often used the phrase: “science is not cheap, but expenditures on it will repay tenfold” [1]. If only Salam had lived a few more years in good health, many more such institutions would have surely come to fruition.

Salam was also a strong supporter of world peace, and thus of nuclear disarmament and Pugwash. Thus, in addition to his numerous awards for his contributions to physics, including the Nobel prize, he also received, some major awards for his contributions to peace and international collaboration, including the Atoms for Peace Award in 1968 and the ”Ettore Majorana” - Science for Peace prize in 1989. It is hard to believe that a single individual can accomplish so much in one lifetime. In this sense, Salam was indeed a rare individual—a phenomenon.

I was especially fortunate to have collaborated with Salam closely for over a decade. Of this period, I treasure most the memory of many moments which were marked by the struggle and the joy of research that we both shared. Needless to say, Salam played a central

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[1] Now named (at this meeting) the Abdus Salam International Centre for Theoretical Physics.
role in the growth of the ideas which we initiated. Let me touch upon one aspect of Salam’s personality. During the ten year period of our collaboration, there have been many letters, faxes, arguments over the phone and in person and even heated exchanges, about tastes and judgements in physics, but always in a good natured spirit. In our discussions, Salam had some favorite phrases. For example, he would sometimes come up with an idea and get excited. If I expressed that I did not like it for such and such reason, he would get impatient and say to me: ”My dear sir, what do you want: Blood?” I would sometimes reply by saying: ”No Professor Salam, I would like something better”. Whether I was right or wrong, he never took it ill. It is this attitude on his part that led to a healthy collaboration and a strong bond between us. Most important for me, by providing strong encouragement from the beginning, yet often arguing, he could bring out the best in a collaborator. For this I will remain grateful to him.

By way of paying tribute to Salam therefore, I would first like to recall briefly the ideas on higher unification which we initiated (Sec. 2), and then present their current status in the context of subsequent experimental and theoretical developments (Secs. 3,4, and 5). The experiments of special relevance are: (a) recent observation of neutrino oscillation at SuperKamiokande, (b) the precision measurements of the gauge couplings at LEP, and (c) ongoing searches for proton decay.

In Section 3, I discuss how the recent discovery of atmospheric neutrino-oscillation at SuperKamiokande, especially the mass of $\nu_\tau$ suggested by the SuperK result, on the one hand agrees well with the gauge coupling unification revealed by the extrapolation of the LEP data, and on the other hand provides clear support for the route to higher unification based on the concepts of SU(4)-color and left-right symmetry. On the theoretical side, the major developments of the last two decades are the ideas of supersymmetry, superstrings, and now M-theory. I will briefly remark how these later developments fully retain the basic ideas of higher unification of the 70’s, and at the same time, provide a substantially new

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3A brief account of how our collaboration evolved in the initial phase is given in my article in the Proceedings of the Salamfestschrift [2] which was held here at ICTP in 1993 (that is probably the last scientific meeting that Salam attended), and a shorter version is given in the article written in his honor after he passed away [3]. The first section of this talk is based in part on these two articles.

4While the SuperKamiokande discovery occurred some six months after the presentation of this talk, its implications are included here because they are so directly relevant to the unification ideas proposed in the early 70’s.
perspective because they unify gravity with the other three forces (Sec.4). The change in perspective pertains to both gauge coupling unification and proton decay. In discussing the puzzle of proton-longevity in supersymmetry, I remark, following recent work, how string-derived symmetries play an essential role in providing a natural resolution of this puzzle (Sec. 5). In the last section, I present the results of two recent papers by Babu, Wilczek and me, that exhibit a strong link between neutrino masses and proton decay in the context of supersymmetric unification (Sec. 6). Based on these works, I remark that the observation of coupling unification as well as the discovery of neutrino-oscillation at SuperK strengthen our expectations for discovery of proton decay in the near future.

II. Status of Particle Physics in 1972: The Growth of New Ideas

IIA. The collaborative research of Salam and myself started during my short visit to Trieste in the summer of 1972. At this time, the electroweak SU(2) × U(1)-theory existed [4], but there was no clear idea of the origin of the fundamental strong interaction. The latter was thought to be generated, for example, by the vector bosons (ρ, ω, K* and φ), or even the spin-o mesons (π, K, η, η', σ), assumed to be elementary, or a neutral U(1) vector gluon coupled universally to all the quarks [5]. Even the existence of the SU(3)-color degree of freedom [3, 4] as a global symmetry was not commonly accepted, because many thought that this would require an undue proliferation of elementary entities. And, of course, asymptotic freedom had not yet been discovered.

In the context of this background, the SU(2) × U(1) theory itself appeared (to us) as grossly incomplete, even in its gauge-sector (not to mention the Higgs sector), because it possessed a set of scattered multiplets, involving quark and lepton fields, with rather peculiar assignment of their weak hypercharge quantum numbers. To remove these shortcomings, we wished: (a) to find a higher symmetry-structure that would organize the scattered multiplets together, and explain the seemingly arbitrary assignment of their weak hypercharges; (b) to provide a rationale for the co-existence of quarks and leptons; further (c) to find a reason for the existence of the weak, electromagnetic as well as strong interactions, by generating the three forces together by a unifying gauge principle; and finally (d) to understand the quantization of electric charge, regardless of the choice of the multiplets, in a way which
should also explain why $Q_{\text{electron}} = -Q_{\text{proton}}$.

We realized that in order to meet these *four aesthetic demands*, the following rather unconventional ideas would have to be introduced:

(i) First, one must place quarks and leptons within the same multiplet and gauge the symmetry group of this multiplet to generate simultaneously weak, electromagnetic and strong interactions \[8, 9\].

(ii) Second, the most attractive manner of placing quarks and leptons in the same multiplet, it appeared to us \[8\], was to assume that quarks do possess the SU(3)-color degree of freedom, and to extend SU(3)-color to the symmetry SU(4)-color, interpreting lepton number as the fourth color. A *dynamical unification of quarks and leptons is thus provided by gauging the full symmetry SU(4)-color*. The spontaneous breaking of SU(4)-color to $SU(3)^c \times U(1)_{B-L}$ at a sufficiently high mass-scale, which makes leptoquark gauge bosons superheavy, was then suggested to explain the apparent distinction between quarks and leptons, as regards their response to strong interactions at low energies. Such a distinction should then disappear at appropriately high energies.

Within this picture, one had no choice but to view *fundamental* strong interactions of quarks as having their origin entirely in the octet of gluons associated with the SU(3)-color gauge symmetry In short, as a *by-product* of our attempts to achieve a higher unification through SU(4)-color, we were led to conclude that low energy electroweak and fundamental strong interactions must be generated by the *combined gauge symmetry SU(2)_L \times U(1)_Y \times SU(3)^C*, which now constitutes the symmetry of the standard model \[8, 10, 11\]. It of course contains the electroweak symmetry $SU(2)_L \times U(1)_Y$ \[4\]. The idea of the SU(3)-color gauge force became even more compelling with the discovery of asymptotic freedom about nine months later \[12\], which explained approximate scaling in deep inelastic ep-scattering, observed at SLAC.

(iii) Third, it became clear that together with SU(4)-color one must gauge the commuting left-right symmetric gauge structure $SU(2)_L \times SU(2)_R$, rather than $SU(2)_L \times U(1)_{I_{3R}}$, so that electric charge is quantized. In short the route to higher unification should include

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\[5\]We thought that if one could understand why the electron and the proton have equal and opposite charges, one would have an answer to Feynman’s question as to why it is that the electron and the proton - rather than the positron and proton - exhibit the same sign of longitudinal polarization in $\beta$-decay. The V-A theory of weak interactions did not provide an *a priori* reason for a choice in this regard.
minimally the gauge symmetry \[ G(224) = SU(2)_L \times SU(2)_R \times SU(4)^C \] with respect to which all members of the electron-family fall into the neat pattern:

\[
F^{e}_{L,R} = \begin{bmatrix}
    u_r & u_y & u_b & \nu_e \\
    d_r & d_y & d_b & e^-
\end{bmatrix}_{L,R}.
\] (2)

With respect to \( G(224) \), the left-right-conjugate multiplets \( F^e_L \) and \( F^e_R \) transform as \((2,1,4)\) and \((1,2,4)\) respectively; likewise for the mu and the tau families.

Viewed against the background of particle physics of 1972, as mentioned above the symmetry structure \( G(224) \) brought some attractive features to particle physics for the first time. They are:

(i) Organization of all members of a family \((8_L + 8_R)\) within one left-right self-conjugate multiplet, with their peculiar hypercharges fully explained.

(ii) Quantization of electric charge, explaining why \( Q_{\text{electron}} = -Q_{\text{proton}} \).

(iii) Quark-lepton unification through \( SU(4) \)-color.

(iv) Left-Right and Particle-Antiparticle Symmetries in the Fundamental Laws: With the left-right symmetric gauge structure \( SU(2)_L \times SU(2)_R \), as opposed to \( SU(2)_L \times U(1)_Y \), it was natural to postulate that at the deepest level nature respects parity and charge conjugation, which are violated only spontaneously \( \cite{9,13} \). Thus, within the symmetry-structure \( G(224) \), quark-lepton distinction and parity violation may be viewed as low-energy phenomena which should disappear at sufficiently high energies.

(v) Existence of Right-Handed Neutrinos: Within \( G(224) \), there must exist the right-handed (RH) neutrino \( (\nu_R) \), accompanying the left-handed one \( (\nu_L) \), for each family, because \( \nu_R \) is the fourth color - partner of the corresponding RH up- quarks. It is also the \( SU(2)_R \)-doublet partner of the associated RH charged lepton (see eq. (2)). The RH neutrinos seem to be essential now (see later discussions) for understanding the non-vanishing light masses of the neutrinos, as suggested by the recent observations of neutrino-oscillations.

(vi) B-L as a local Gauge Symmetry: \( SU(4) \)-color introduces B-L as a local gauge symmetry. Thus, following the limits from Eötvos experiments, one can argue that B-L must be violated spontaneously. It has been realized, in the light of recent works on electroweak sphaleron effects, that such spontaneous violation of B-L may well be needed to implement baryogenesis via leptogenesis \( \cite{14} \).
(vii) **Proton Decay: The Hall-Mark of Quark-Lepton Unification:**

We recognized that the spontaneous violation of B-L, mentioned above, is a reflection of a more general feature of non-conservations of baryon and lepton numbers in unified gauge theories, including those going beyond G(224), which group quarks and leptons in the same multiplet \[9, 15\]. Depending upon the nature of the gauge symmetry and the multiplet-structure, the violations of B and/or L could be either spontaneous \(^6\), as is the case for the non-conservation of B-L in SU(4) color, and those of B and L in the maximal one-family symmetry like SU(16) \[16\]; alternatively, the violations could be explicit, which is what happens for the subgroups of SU(16), like SU(5) \[17\] or SO(10) \[18\] (see below). One way or another baryon and/or lepton-conservation laws cannot be absolute, in the context of such higher unification. The simplest manifestation of this non-conservation is proton decay \((\Delta B \neq 0, \Delta L \neq 0)\); the other is the Majorana mass of the RH neutrinos \((\Delta B = 0, \Delta L \neq 0)\), as is encountered in the context of G(224) or SO(10). An unstable proton thus emerges as the crucial prediction of quark-lepton unification \[9, 17\]. Its decay rate would of course depend upon more details including the scale of such higher unification.

IIB. **Going Beyond G(224): SO(10) and SU(5)**

To realize the idea of a single gauge coupling governing the three forces \[8, 17\], one must embed the standard model symmetry, or G(224), in a simple or effectively simple group (like \(SU(N) \times SU(N)\)). Several examples of such groups have been proposed. Howard Georgi and Sheldon Glashow proposed the first such group SU(5) \[17\] which embeds the standard model symmetry, but not G(224). Following the discovery of asymptotic freedom of nonabelian gauge theories \[12\] and the suggestion of SU(5), Georgi, Helen Quinn and Weinberg showed how renormalization effects, following spontaneous breaking of the unification symmetry, can account for the observed disparity between the three gauge couplings at low energies \[19\]. Each of these contributions played a crucial role in strengthening the ideas of higher unification.

To embed G(224) into a simple group, it may be noted that it is isomorphic to SO(4)
Thus the smallest simple group to which it can be embedded is SO(10). By the time SO(10) was proposed, all the advantages of G(224) [(i) to (vi), listed above] and the ideas of higher unification were in place. Since SO(10) contains G(224), the features (i) to (vi) are of course retained by SO(10). In addition, the 16-fold left-right conjugate set ($F_L^e + \bar{F}_R^e$) of G(224) corresponds to the spinorial 16 of SO(10). Thus, SO(10) preserves even the 16-plet family-structure of G(224), without a need for any extension. If one extends G(224) to the still higher symmetry E$_6$, the advantages (i) to (vi) are retained, as in SO(10), but in this case, one must extend the family-structure from a 16 to a 27-plet.

Some distinctions between SU(5) on the one hand versus G(224) or SO(10) on the other hand are worth noting. Historically, SU(5) served an important purpose, being the smallest symmetry that embodies the essential ideas of higher unification. However, it split members of a family into two multiplets: $\bar{5} + 10$. By contrast, SO(10) groups all 16 members of a family into one multiplet. Likewise, G(224), subject to the assumption that parity is a good symmetry at high energies, groups the 16 members into one L-R self-conjugate multiplet. Furthermore, in contrast to G(224) and SO(10), SU(5) violates parity explicitly from the start; it does not contain SU(4)-color, and therefore does not possess B-L as a local symmetry; and the RH neutrino is not an integral feature of SU(5). As I discuss below, these distinctions turn out to be especially relevant to considerations of neutrino masses.

Comparing G(224) with SO(10), as mentioned above, SO(10) possesses all the features (i) to (vi) of G(224), but in addition it offers gauge coupling unification. I should, however, mention at this point that the perspective on coupling unification and proton decay changes considerably in the context of supersymmetry and superstrings. In balance, a string-derived G(224) offers some advantages over a string-derived SO(10), while the reverse is true as well. Thus, it seems that a definite choice of one over the other is hard to make at this point. I will return to this discussion in Secs. 4 and 5.
III. Neutrino Masses: Evidence in Favor of the G(224) Route to Higher Unification

Leaving aside the differences between alternative routes to higher unification, based purely on aesthetic taste, it was of course not clear in the early 70’s as to whether the special features of G(224) — i.e. SU(4)-color, left-right symmetry and the RH neutrino — are utilized by nature. The situation has, however, changed owing to the recent SuperKamiokande (SK) discovery of the oscillation of $\nu_\mu$ to $\nu_\tau$ (or $\nu_X$), with a value of $\delta m^2 \approx \frac{1}{2}(10^{-2} - 10^{-3})eV^2$ and an oscillation-angle $sin^22\theta > 0.82$. One can argue (see e.g. [22]) that the SK result, especially the value of $\delta m^2$, clearly points to the need for the existence of the RH neutrinos, accompanying the observed LH ones. If one then asks the question: What symmetry on the one hand dictates the existence of the RH neutrinos, and on the other hand also ensures quantization of electric charge, together with quark-lepton unification, one is led to two very beautiful conclusions: (i) quarks and leptons must be unified minimally within the symmetry SU(4)-color, and that, (ii) deep down, the fundamental theory should possess a left-right symmetric gauge structure: SU(2)$_L \times$ SU(2)$_R$. In short, the standard model symmetry must be extended minimally to G(224).

One can now obtain an estimate for the mass of $\nu^L_\tau$ in the context of G(224) or SO(10) by using the following three steps [22]:

(i) First, assume that B-L and $I_{3R}$, contained in a string-derived G(224) or SO(10), break near the unification-scale:

$$M_X \sim 2 \times 10^{16}GeV,$$

(3)

through Higgs multiplets of the type suggested by string-solutions [23] — i.e. $<(1,2,4)_H>$ for G(224) or $<\overline{16}_H>$ for SO(10). (The "empirical" determinations of $M_X$ and the new perspective on unification due to supersymmetry as well as superstrings are discussed in the next section). In the process, the RH neutrinos ($\nu^i_R$), which are singlets of the standard model, can and generically will acquire superheavy Majorana masses of the type $M^i_R \nu^{iT}_R C^{-1} \nu^i_R$, by utilizing the VEV of $<\overline{16}_H>$ and effective couplings of the form:

$$L_M(SO(10)) = \lambda_R^{ij} 16_i \cdot \overline{16}_i \cdot \overline{16}_j / M_{Pl} + hc$$

(4)

A similar expression holds for G(224). Here i,j=1,2,3, correspond respectively to $e, \mu$ and $\tau$ families; $M_{Pl}$ denotes the reduced Planck mass $\simeq 2 \times 10^{18}GeV$. Such gauge-invariant non-
renormalizable couplings might be expected to be induced by Planck-scale physics. (They may well arise - in part or dominantly - by renormalizable interactions through tree-level exchange of superheavy states, such as those in the string tower). Assuming that the Majorana couplings are family-hierarchical, $\lambda_{33}$ being the leading one, somewhat analogous to those that give the Dirac masses, and ignoring the effects of off-diagonal mixings (for simplicity), one obtains:

$$M_{3R} \approx \frac{\lambda_{33} \langle \bar{16}_H \rangle^2}{2 \times 10^{18} \text{GeV}} \approx \lambda_{33}(4.5 \times 10^{14} \text{GeV})\eta^2$$  \hspace{1cm} (5)

This is the Majorana mass of the RH tau neutrino. Guided by the value of $M_X$, in this estimate, we have substituted $\langle \bar{16}_H \rangle = (3 \times 10^{16} \text{GeV})\eta$ where $\eta \approx 1/2$ to 2.

(ii) Second, assume that the effective gauge symmetry below the string-scale contains SU(4)-color. Now using SU(4)-color and the Higgs multiplet $(2, 2, 1)_H$ of G(224) or equivalently $10_H$ of SO(10), one obtains the relation $m_\tau(M_X) = m_b(M_X)$, which is known to be successful. Thus, there is a good reason to believe that the third family gets its masses primarily from the $10_H$ or equivalently $(2, 2, 1)_H$. In turn, this implies:

$$m(\nu_D^\tau) \approx m_{\text{top}}(M_X) \approx (100 - 120) \text{GeV}$$  \hspace{1cm} (6)

(iii) Given the superheavy Majorana masses of the RH neutrinos as well as the Dirac masses, as above, the see-saw mechanism [24] yields naturally light masses for the LH neutrinos. For $\nu_L^\tau$ (ignoring mixing), one thus obtains, using eqs. (5) and (6),

$$m(\nu_L^\tau) \approx \frac{m(\nu_D^\tau)^2}{M_{3R}} \approx (1/45) \text{eV}(1 \text{ to } 1.44)/\lambda_{33}\eta^2$$  \hspace{1cm} (7)

Considering that on the basis of the see-saw mechanism, we naturally expect that $m(\nu_L^\tau) \ll m(\nu_D^\tau) \ll m(\nu_L^\tau)$, and assuming that the SuperK observation represents $\nu_L^\mu - \nu_L^\tau$ (rather than $\nu_L^\mu - \nu_X$) oscillation, so that the observed $\delta m^2 \approx 1/2(10^{-2} - 10^{-3}) \text{eV}^2$ corresponds to $m(\nu_L^\tau)_{\text{obs}} \approx (1/15 \text{ to } 1/40) \text{ eV}$, it seems truly remarkable that the expected magnitude of $m(\nu_L^\tau)$, given by eq.(7), is just about what is observed, if $\lambda_{33}\eta^2 \approx 1$ to 1/3. Such a range of $\lambda_{33}\eta^2$ seems most plausible and natural (see discussion in Ref. [22]). It should be stressed that the estimate (7) utilizes the ideas of supersymmetric unification, especially in getting the scale of $M_X$ (eq.(3)), and of SU(4)-color in getting $m(\nu_{\text{Dirac}}^\tau)$ (eq.(6)). The agreement between the expected and the SuperK result thus suggests that, at a deeper level, near the string or the coupling unification scale $M_X$, the symmetry group G(224) and thus the ideas of SU(4)-color and left-right symmetry are likely to be relevant to nature.
By providing clear support for G(224), the SK result selects out SO(10) or $E_6$ as the underlying grand unification symmetry, rather than SU(5). Either SO(10) or $E_6$ or both of these symmetries ought to be relevant at some scale, and in the string context, as discussed later, that may well be in higher dimensions, above the compactification-scale, below which there need be no more than just the G(224)-symmetry. If, on the other hand, SU(5) were regarded as a fundamental symmetry, first, there would be no compelling reason, based on symmetry alone, to introduce a $\nu_R$, because it is a singlet of SU(5). Second, even if one did introduce $\nu_R^i$ by hand, the Dirac masses, arising from the coupling $h^5_i < 5_H > \nu_R^i$, would be unrelated to the up-flavor masses and thus rather arbitrary (contrast with eq. (6)). So also would be the Majorana masses of the $\nu_R^i$’s, which are SU(5)-invariant and thus can even be of order Planck scale (contrast with Eq. (5)). This would give $m(\nu^i_L)$ in gross conflict with the observed value. In this sense, the SK result appears to disfavor SU(5) as a fundamental symmetry, with or without supersymmetry.

Finally, it is intriguing to note that the SuperK result agrees well with the idea of supersymmetric unification. For this purpose, one could use the mass of $m(\nu^i_L)$, suggested by the SuperK data, as an input to obtain the VEV of $< \bar{1}6_H >$, that breaks B-L, as an output. By reversing the steps in going from eq. (7) together with eqs. (6) and (5), one obtains, as is to be expected, $< \bar{1}6_H > \sim 3 \times 10^{16}$ GeV (if $\lambda_{33} \sim O(1)$). It is rather striking that this is just about the same as the scale of the meeting of the three gauge couplings, which is obtained from extrapolation of their measured value at LEP, in the context of supersymmetry (see next section). In short, two very different considerations — light neutrino masses on the one hand, and gauge coupling meeting on the other hand — point to one and the same scale for the underlying new physics! If one assumes supersymmetric unification, one can hardly avoid noticing how beautifully it makes the picture hang together!

In the foregoing, I have discussed only the mass of $\nu_\tau$ in the context of G(224) or SO(10). In the last section, I will mention briefly how, by adopting familiar ideas of understanding cabibbo-like mixing angles in the quark-sector, one can quite plausibly obtain not only the right magnitude for the mass of $\nu_\tau$ but also a large $\nu^i_L - \nu^i_L$ oscillation angle, as observed at SuperK. I will also discuss that simultaneously one can attribute the solar neutrino-deficit to $\nu_e - \nu_\mu$ oscillation.

I now present the issues associated with coupling unification.
IV. Coupling Unification: A New Perspective Due To Supersymmetry and Superstrings

It has been recognized from the early 70’s, that the concept of higher unification — now commonly called grand unification — has two dramatic consequences: (i) meeting of the gauge couplings at a high scale, and (ii) proton decay \[8, 9, 16, 19\]. Equally dramatic is the prediction of the light neutrino masses, which is a special feature of only a subclass of grand unification symmetries that contain SU(4)-color, like SO(10) or \(E_6\). As discussed above, this feature seems to be borne out by the SuperKamiokande result on neutrino-oscillations. The status of the first two predictions are discussed in this section and the next.

IVA. Meeting of The Three Gauge Couplings and The Need for Supersymmetry

It has been known for some time that the precision measurements of the standard model coupling constants (in particular \(\sin^2 \theta_W\)) at LEP put severe constraints on the idea of grand unification. Owing to these constraints, the non-supersymmetric minimal \(SU(5)\), and for similar reasons, the one-step breaking minimal non-supersymmetric \(SO(10)\)-model as well, are now excluded.\[25\] For example, minimal non-SUSY \(SU(5)\) predicts: \(\sin^2 \theta_W(m_Z)\big|_{\overline{MS}} = 0.214 \pm 0.004\), whereas current experimental data show: \(\sin^2 \theta_W(m_Z)_{\text{exp,LEP}} = 0.2313 \pm 0.0003\). The disagreement with respect to \(\sin^2 \theta_W\) is reflected most clearly by the fact that the three gauge couplings \((g_1, g_2, g_3)\), extrapolated from below, fail to meet by a fairly wide margin in the context of minimal non-supersymmetric \(SU(5)\) (see fig. 1).

But the situation changes radically if one assumes that the standard model is replaced by the minimal supersymmetric standard model (MSSM), above a threshold of about 1\(TeV\). In this case, the three gauge couplings are found to meet\[26\], at least approximately, provided \(\alpha_3(m_Z)\) is not too low (see figs. 2a and 2b). Their scale of meeting is given by

\[
M_X \approx 2 \times 10^{16} GeV \quad \text{(MSSM or SUSYSU(5))}
\] (8)

\(M_X\) may be interpreted as the scale where a supersymmetric grand unification symmetry (GUT) (like minimal SUSY \(SU(5)\) or \(SO(10)\)) — breaks spontaneously into the supersymmetric standard model symmetry \(SU(2)_L \times U(1) \times SU(3)^c\).
The dramatic meeting of the three gauge couplings (Fig. 2) thus provides a strong support for both grand unification and supersymmetry.

Considering (a) that a straightforward meeting of the three gauge couplings occurs, only provided supersymmetry is assumed; (b) that supersymmetry provides at least a technical resolution of the gauge hierarchy problem, by preserving the small input value of the ratio of \((m_W/M_X)\), in spite of quantum corrections; and (c) that it is needed for consistency of string theory, it seems apparent that supersymmetry is an essential ingredient for higher unification.

IVB. The Issue of Compatibility Between MSSM and String Unifications

The idea of grand unification would be incomplete without incorporating the unity of gravity with the weak, electromagnetic and the strong QCD forces. Superstring theory [27], and now the M theory [28] provide however the only known framework that exhibits the scope for such a unity. It thus becomes imperative that the meeting of the gauge couplings of the three non-gravitational forces, which occur by the extrapolation of the LEP data in the context of MSSM, be compatible with string unification.

Now, string theory does provide gauge coupling unification for the effective gauge symmetry, below the compactification-scale. The new feature is that even if the effective symmetry is not simple, like SU(5) or SO(10), but instead is of the form G(213) or G(224) (say), the gauge couplings of G(213) or G(224) should still exhibit familiar unification at the string-scale, for compactification involving appropriate Kac-Moody levels (i.e. \(k_2 = k_3 = 1, k_Y = \frac{5}{3}\) for G(213)), barring of course string-threshold corrections [29]. And even more, the gauge couplings unify with the gravitational coupling \((\frac{8\pi G_N}{\alpha'})\) as well at the string scale, where \(G_N\) is the Newton’s constant and \(\alpha'\) is the Regge slope.

Thus one can realize coupling unification without having a GUT-like symmetry below the compactification scale. This is the new perspective brought forth by string theory. There is, however, an issue to be resolved. Whereas the MSSM-unification scale, obtained by extrapolation of low energy data is given by \(M_X \approx 2 \times 10^{16} \text{ GeV}\), the expected one-loop level string-unification scale [29] of \(M_{st} \approx g_{st} \times (5.2 \times 10^{17} \text{ GeV}) \approx 3.6 \times 10^{17} \text{ GeV}\) is about twenty times higher [30, 31]. Here, one has used \(\alpha_{st} \approx \alpha_{GUT} \text{ (MSSM)} \approx 0.04\).
A few alternative suggestions which have been proposed to remove this mismatch by nearly a factor of 20 between $M_X$ and $M_{st}$, are as follows:

**Matching Through String-Duality:** One suggestion in this regard is due to Witten [32]. Using the equivalence of the strongly coupled heterotic $SO(32)$ and the $E_8 \times E_8$ superstring theories in $D = 10$, respectively to the weakly coupled $D = 10$ Type I and an eleven-dimensional $M$–theory, he observed that the 4-dimensional gauge coupling and $M_{st}$ can both be small, as suggested by MSSM extrapolation of the low energy data, without making the Newton’s constant unacceptably large.

**Matching Through String GUT:** A second way in which the mismatch between $M_X$ and $M_{st}$ could be resolved is if superstrings yield an intact supersymmetric grand unification symmetry like $SU(5)$ or $SO(10)$ with the right spectrum – i.e., three chiral families and a suitable Higgs system $M_{st}$ [33], and if this symmetry would break spontaneously at $M_X \approx (1/20$ to $1/50)M_{st}$ to the standard model symmetry. However, as yet, there is no realistic, or even close-to realistic, string–derived GUT model [33]. In particular, to date, no string-derived solution exists with a resolution of the doublet-triplet splitting problem, without which one faces the problem of rapid proton decay (see discussions later).

**Matching Through Intermediate Scale Matter:** A third alternative is based on string–derived standard model–like gauge groups. It attributes the mismatch between $M_X$ and $M_{st}$ to the existence of new matter with intermediate scale masses ($\sim 10^{9} – 10^{13}$ GeV), which may emerge from strings [34]. Such a resolution is in principle possible, but it would rely on the delicate balance between the shifts in the three couplings and on the existence of very heavy new matter which in practice cannot be directly tested by experiments.

**Matching Through ESSM – A Case for Semi-Perturbative Unification:**

Babu and I suggested that a resolution of the mismatch between $M_X$ and $M_{st}$ can come about if there exists two "light" vector-like families $(16 + \overline{16})$ at the TeV scale [35]. Such a spectrum has an apriori motivation in that it provides a simple reason for inter-family mass-hierarchy. It can also be tested at LHC. Including two and even three-loop effects [36], this spectrum leads to a semi-perturbative unification, with $\alpha_{GUT} \approx .2 – .3$, and raises $M_X$ to $(1 - 2) \times 10^{17}$ GeV. Such higher values of $\alpha_{GUT}$ (compared to .04 for MSSM) may provide an additional advantage by helping to stabilize the dilaton.

While each of the solutions mentioned above possesses a certain degree of plausibility (see Ref. 31 for some additional possibilities), it is far from clear which, if any, is utilized by
the true string-vacuum. This is of course related to the fact that, as yet, there is no insight as to how the vacuum is selected in the string or in the M-theory.

In summary, string theory, as well as M-theory, fully retain the basic concept of grand unification — i.e. unification of matter and of its gauge forces. But they enrich the scope considerably by (a) unifying all matter of spins 0, 1/2, 1, 3/2, 2 and higher, and (b) unifying gravity with the other forces. As noted above, the perspective on gauge coupling unification however changes in the string context, because such a unification can occur at the string scale, even without having a GUT-like symmetry at that scale. In the next section, I discuss the advantages as well as possible disadvantages of GUT versus non-GUT string solutions, keeping in mind the issues of both coupling unification and rapid proton decay.

I now turn to considerations of proton decay.

V. Proton Decay as a Probe to Higher Unification

VA. As mentioned before, one of the hallmarks of grand unification is non-conservation of baryon and lepton numbers, which for most simple models, lead to proton decay [9, 17]. The general complexion of baryon and lepton number non-conserving processes, including alternative modes of proton decay, $n \rightarrow \bar{n}$ oscillation and neutrinoless double beta decay is discussed in my talk at the Oak Ridge Conference [37]. Here I will focus on proton decay.

Almost 25 years have passed since the suggestion of proton decay was first made in the context of unified theories, in 1973. While there was considerable resistance from the theoretical community against such ideas at that point, the psychological barrier against them softened over the years. The growing interest in the prospect of such a decay thus led to the building of proton-decay detectors in different parts of the world, including the most sensitive one of the 80’s (IMB) at Cleveland, followed by Kamiokande in Japan. While proton decay is yet to be discovered, it is encouraging that searches for this decay continues at SuperKamiokande with higher sensitivity than ever before and detectors such as ICARUS are planned to come. The dedicated searches for proton decay at IMB (which was operative till a few years ago) and Kamiokande [38] already put severe constraints on grand unification for over a decade. Owing to these constraints, the non-supersymmetric minimal SU(5) and the minimal SO(10) models as well (with one-step breaking) are now excluded. In particular, conservatively, minimal non-SUSY SU(5) predicts: $\Gamma(p \rightarrow e^+\pi^0)^{-1} \leq (6-10) \times 10^{31}$ yr, where
as current data including those from Superkamiokande [39] yields:

\[ \Gamma(p \to e^+ \pi^0)_{\text{exp}} > 1.6 \times 10^{33} \text{yr}. \]  

(9)

VB. The Issue of Proton-Longevity in SUSY Grand Unification

Although non-supersymmetric minimal SU(5) or SO(10) are excluded by proton-decay searches, as well as by precision measurements of \( \sin^2 \theta_W \), the situation with regard to both issues alters radically, once supersymmetry is combined with the idea of grand unification. First, as mentioned before, SUSY makes it possible for the three gauge couplings to meet at a common scale \( M_X \approx 2 \times 10^{16} \text{ GeV} \). If one uses \( \alpha_3 \) and \( \alpha_2 \) as inputs, it correspondingly leads to the correct prediction for \( \sin^2 \theta_W \).

As regards proton decay, supersymmetric grand unified theories (GUTS), bring two new features: (i) First, by raising \( M_X \) to a higher value compared to the non-supersymmetric case, as above, they strongly suppress the gauge-boson-mediated \( d=6 \) proton decay operators, so that one obtains \( \Gamma(p \to e^+ \pi^0)_{d=6} \approx 10^{30\pm1.5} \text{ yr} \). This is of course compatible with current experimental limits (eq(9)). (ii) Second, they generate \( d=5 \) proton decay operators of the form \( Q_i Q_j Q_k L_\ell / M \) and \( UUDE \) in the superpotential, through the exchange of color triplet Higgsinos, which are the GUT partners of the electroweak Higgsino doublets [40]. These triplets lie, for example, in the \( 5(\bar{5}) \) of SU(5), or in the 10 or SO(10). Since the corresponding amplitudes are damped by just one power of the mass of the color-triplet higgsinos (\( m_{H_c} \)), these \( d=5 \) operators provide the dominant mechanism for proton decay in supersymmetric GUT.

The \( d=5 \) operators have marked effects both on the branching ratios of different decay modes as well as on the rate of proton decay. First, owing to (a) color-antisymmetry, (b) Bose symmetry of the scalar squark and slepton fields, and (c) the family-hierarchical Yukawa couplings, it turns out that these \( d=5 \) operators (to be called ”standard” \( d=5 \)) lead to dominant antineutrino modes:

\[ p \to \bar{\nu}_\mu K^+, \bar{\nu}_\mu \pi^+ \text{ (standard } d = 5), \]

(10)

but highly suppressed \( e^+ \pi^0, e^+ K^0 \) and even \( \mu^+ \pi^0 \) and \( \mu^+ K^0 \) modes (at least for small and moderate \( \tan \beta \leq 15 \)). Recall, by contrast, that for non-supersymmetric GUTS, \( e^+ \pi^0 \) is expected to be the dominant mode.
Second, given the Yukawa couplings of the electroweak Higgs doublets (inferred from fermion masses), a typical contribution to the standard d=5 proton decay operator of the form \(QQQL/M\) is found to have an effective strength \(\approx (m_c m_s \sin \theta_c / v_u v_d) (1/M_{H_c}) \approx 10^{-7} \tan \beta / M_{H_c}\) at the GUT-scale. Now, for plausible values or limits on \(m_{\tilde{q}} \leq 1\) TeV, \((m_{\tilde{W}}/m_{\tilde{q}}) \geq 1/6\) and \(\tan \beta \geq 3\) (say), the d=5 operator, as noted above, subject to wino-dressing, leads to an inverse decay rate \[\Gamma^{-1}(p \to \bar{\nu}_\mu K^+) \leq 3 \times 10^{32}\text{yrs}(\frac{M_{H_c}}{3 \times 10^{16}\text{GeV}})^2\] (11)

To be conservative, this estimate uses the minimum theoretical value of the hadronic matrix element \((\beta_H = 0.003 GeV^3)\), and assumes a cancellation by a factor of two between \(\tilde{t}\) and \(\tilde{c}\)-contributions, (although, in general, one could gain a factor of 2 to 4 (say) in the rate on each count). Given the current experimental limit of \(\Gamma(p \to \bar{\nu}K^+)^{-1} > 5.5 \times 10^{32}\text{ yrs (90\% CL)}\) [42], it follows that the color-triplets must be superheavy. Conservatively [43],

\[M_{H_c} \geq (3 - 5) \times 10^{16}\text{GeV}\] (12)

While the color triplets need to be superheavy, their doublet-partners must still be light \((\leq 1\) TeV). The question arises: How can the color-triplets become superheavy, while the doublet-partners remain naturally light? This is the well-known problem of doublet-triplet splitting that faces all SUSY GUTS.

Leaving out the possibility of extreme fine tuning, two of the proposed solutions to this problem are as follows:

(i) **The Missing Partner Mechanism** [45]: In this case, by introducing suitable large-size Higgs multiplets, such as \(50_H + \overline{50}_H + 75_H\), in addition to \(5_H + \overline{5}_H\) of \(SU(5)\), and introducing couplings of the form \(W = C5_H \cdot \overline{50}_H \cdot <75_H> + D\overline{5}_H \cdot 50_H <75_H>\), one can give superheavy masses to the triplets (anti-triplets) in \(5(\overline{5})\) by pairing them with anti-triplets (triplets) in \(\overline{50}(50)\). But there do not exist doublets in \(50(\overline{50})\) to pair up with the doublets in \(5(\overline{5})\), which therefore remain light.

(ii) **The Dimopoulos-Wilczek Mechanism** [46]: Utilizing the fact that the VEV of \(45_H\) of \(SO(10)\) does not have to be traceless (unlike that of \(24_H\) of \(SU(5)\)), one can give mass to color-triplets and not to doublets in the 10 of \(SO(10)\), by arranging the VEV of \(45_H\) to be proportional to \(i\tau_2 \times \text{diag}(x, x, x, o, o)\), and introducing a coupling of the form \(\lambda 10_{H1} \cdot 45_H \cdot 10_{H2}\) in \(W\). Two 10's are needed owing to the anti-symmetry of 45. Because of two 10's, this
coupling would leave two pairs of electroweak doublets massless. One must, however, make one of these pairs superheavy, by introducing a term like $M_{10}10_{H_2} \cdot 10_{H_2}$ in $W$, so as not to spoil the successful prediction of $\sin^2 \theta_W$ of SUSY GUT. In addition, one must also ensure that only $10_{H_1}$ but not $10_{H_2}$ couple to the light quarks and leptons, so as to prevent rapid proton decay. All of these can be achieved by imposing suitable discrete symmetries. There is, however, still some question as to whether the mass-scale $M_{\text{eff}} \equiv (\lambda < 45_{H_1} >)^2/M_{10}$ that controls the d=5 amplitude can be of order $10^{18}$ GeV (that is needed), without conflicting with unification of the gauge couplings.

In summary, solutions to the problem of doublet-triplet splitting needing a suitable choice of Higgs multiplets and discrete symmetries are technically feasible. It is however not clear whether any of these mechanisms can be consistently derived from an underlying theory, such as the superstring theory. To date, no such mechanism has been realized in a string-derived GUT solution [33].

**VC. Rapid Proton Decay And The Other Problems of Naturalness in Supersymmetry**

In addition to the problem of doublet-triplet splitting that faces SUSY GUT theories, it is important to note that there is a generic problem for all supersymmetric theories, involving either a GUT or a non-GUT symmetry, in the presence of quantum gravity. This is because, in accord with the standard model gauge symmetry $SU(2)_L \times U(1)_Y \times SU(3)^C$, a supersymmetric theory in general permits, in contrast to non-supersymmetric ones, dimension 4 and dimension 5 operators which violate baryon and lepton numbers [40]. Such operators are likely to be induced by Planck-scale physics including especially quantum gravity, unless they are forbidden by symmetries of the theory. Using standard notations, the operators in question are as follows:

$$W = [\eta_1 U \overline{U} \overline{D} + \eta_2 Q \overline{L} \overline{D} + \eta_3 L \overline{L} \overline{E}]$$

$$+ [\lambda_1 QQQL + \lambda_2 U \overline{U} \overline{D} \overline{E} + \lambda_3 LLH_2 H_2]/M. \quad (13)$$

Here, generation, $SU(2)_L$ and $SU(3)^C$ indices are suppressed. $M$ denotes a characteristic mass scale. The first two terms of $d = 4$, jointly, as well as the $d = 5$ terms of strengths $\lambda_1$ and $\lambda_2$, individually, induce $\Delta(B - L) = 0$ proton decay with amplitudes $\sim \eta_1 \eta_2/m_{\tilde{g}}^2$.
and \((\lambda_{1,2}/M)(\delta)\) respectively, where \(\delta\) represents a loop-factor. Experimental limits on proton lifetime turn out to impose the constraints: \(\eta_1\eta_2 \leq 10^{-24}\) and \((\lambda_{1,2}/M) \leq 10^{-23}\) to \(10^{-24}\) GeV\(^{-1}\). Thus, even if \(M \sim M_{string} \sim 10^{18}\) GeV, we must have \(\lambda_{1,2} \leq 10^{-5}\) to \(10^{-6}\), so that proton lifetime will be in accord with experimental limits.

Renormalizable, supersymmetric standard-like and \(SU(5)\) \cite{14} models can be constructed so as to avoid, by choice, the \(d = 4\) operators (i.e. the \(\eta_{1,2,3}\)-terms) by imposing a discrete or a multiplicative \(R\)-parity symmetry: \(R \equiv (-1)^{3(B-L)}\), or more naturally, by gauging \(B-L\), as in \(\mathcal{G}_{224} \equiv SU(2)_L \times SU(2)_R \times SU(4)^C\) or \(SO(10)\). Such resolutions, however, do not in general suffice if we permit higher dimensional operators and intermediate or GUT-scale VEVs of fields which violate \((B-L)\) by one unit and thereby \(R\)-parity (see below). In string solutions, VEV’s of such fields seem to be needed, to generate Majorana masses for the RH neutrinos. Besides, \(B-L\) can not provide any protection against the \(d = 5\) operators given by the \(\lambda_1\) and \(\lambda_2\) - terms, which conserve \(B-L\). As mentioned above these operators are, however, expected to be present in any theory linked with gravity, e.g. a superstring theory, unless they are forbidden by some new symmetries.

These considerations show that, in the context of supersymmetry, the extraordinary stability of the proton is a major puzzle. And, the problem is heightened especially in the context of SUSY GUT theories because of the need for the doublet-triplet splitting in such theories. \textit{The question in fact arises: Why does the proton have a lifetime exceeding} \(10^{40}\) \text{sec}, \textit{rather than the apparently natural value, for supersymmetry, of less than 1 sec}? As such, the known longevity of the proton deserves a natural explanation. I believe that it is in fact a major clue to some deeper physics that operates near the Planck-scale.

Apart from the problem of rapid proton decay, supersymmetry in fact generates a few additional problems of similar magnitude. These together constitute the so-called \textit{naturalness problems of supersymmetry}. They include understanding: (i) the extreme smallness of the SUSY-breaking mass- splittings compared to the Planck-scale (i.e. why \((\delta m_s/M_{planck}) \sim 10^{-15}\) rather than order unity), (ii) the smallness of the \(\mu\)-parameter of MSSM also compared to the Planck-scale, (iii) the strong suppression of the neutrino-Higgsino mixing mass, (that needs to be less than about 1 MeV) in a context where R-parity is violated, and (iv) the smallness of especially the CP- violating part of the \(K^0 - \bar{K}^0\) amplitude in spite of the potentially large contributions from squark and gluino loops. In addition to this set of problems, which are special to supersymmetry, there is of course the familiar challenge of
understanding the hierarchical masses and mixings of quarks and leptons. Resolving these problems would amount to understanding the origins of some extremely small numbers, ranging from $10^{-6}$ to $10^{-19}$, which apriori could be of order unity. As such, I believe that they are a reflection of new symmetries which operate near the Planck-scale. In the limit of these symmetries, the respective entities, such as the strengths of the d=4 and d=5 operators and the magnitudes of $\delta m_s$ and $\mu$, would vanish. Although the symmetries break, quite possibly near the GUT-scale, they need to be powerful enough to provide the needed protection up to sufficiently high order in non-renormalizable terms, scaled by the Planck mass, so as to render the respective numbers as small as they are. Symmetries of this nature simply do not exist in conventional GUTS. They do, however, arise, not so infrequently, in string-solutions, including some which are fairly realistic, possessing three-families and hierarchical Yukawa couplings \cite{47, 48, 49}.

Invariably, these solutions possess non-GUT symmetries such as (i) the (B-L)-preserving standard model-like symmetry G(2113) \cite{47}, or (ii) G(224) \cite{48}, or (iii) flipped SU(5) $\times$ U(1) \cite{49}. Based on some recent work \cite{50}, I note below how string symmetries can play an essential role in avoiding the danger of rapid proton decay and also help in resolving some of the other naturalness problems noted above.

**VD. The Role of String-Flavor Symmetries in Resolving The Naturalness Problems**

To illustrate the usefulness of string-symmetries, I would consider especially a class of three-family string solutions which are based on the free fermionic construction \cite{51} and correspond to a special $Z_2 \times Z_2$ orbifold compactification \cite{47}. They lead, after the applications of all GSO-projections, to a gauge symmetry at the string-scale of the form:

$$G_{st} = [SU(2)_L \times SU(3)^C \times U(1)_{t_{3R}} \times U(1)_{B-L}] \times [G_M = \prod_{i=1}^{6} U(1)_i] \times G_H. \quad (14)$$

The first factor will be abbreviated as G(2113). Here $U(1)_i$ denote six horizontal symmetries which act non-trivially on the three families ($e, \mu$ and $\tau$) and distinguish between them. $G_H$ denotes the hidden-sector symmetry which operate on ”hidden” matter. The horizontal symmetries $U(1)_i$, couple to both the observable and the hidden sector matter.

The crucial point is that the pairs $(U_1, U_4)$, $(U_2, U_5)$ and $(U_3, U_6)$, respectively couple
to families 1, 2 and 3, in an identical fashion. \[7\] Thus, on the one hand, these six U(1) symmetries, having their origin in SO(44) \[51\], distinguish between the three families, unlike a GUT symmetry like SO(10). Thereby they serve as generalized "flavor" symmetries and in turn help explain the hierarchical Yukawa couplings of the three families \[17\]. On the other hand, the coupling of the three pairs \((U_1, U_4), (U_2, U_5)\) and \((U_3, U_6)\) fully preserve the cyclic permutation symmetry with respect to the three families.

Turning to the problem of rapid proton decay in the context of these string solutions, there are two features which together help resolve the problem. First, it turns out that for non-GUT solutions of the type obtained in Ref. \[47\] (this is also true of the G(224)-solution of Ref. \[48\]), in the process of compactification leading to G(2113), the dangerous color triplets are simply projected out of the spectrum altogether. As a result, the problem of doublet-triplet splitting is neatly avoided. This is an obvious advantage of a non-GUT over a GUT string solution.

Second, it needs to be said that of the six U(1)'s \[Ref. 47\], one linear combination — i.e. \(U(1)_A = 1/\sqrt{15}[2(U_1 + U_2 + U_3) - (U_4 + U_5 + U_6)]\) — is anomalous, while the other five are anomaly-free (occurrence of such anomalous U(1) is in fact fairly generic in string solutions). Furthermore, the string solutions invariably yield a set of standard model singlet fields \(\{\Phi_a\}\) which couple to the flavor symmetries \(U(1)_i\). For the solution of Ref. 47, they couple to the six U(1)'s as well as to B-L and \(I_{3R}\). Now a set of these \(\{\Phi_i\}\) fields must acquire VEV's of order \((10^{-1} - 10^{-2}) \, M_{pl}\) (where \(M_{pl} \approx 2 \times 10^{18} \text{ GeV}\)), in order to cancel the Fayet-Iliopoulos D-term generated by \(U(1)_A\), and also all F and D-terms, so that supersymmetry is preserved, barring additional constraints \[52\].

It turns out that the six flavor symmetries \(U(1)_i\), together with certain SUSY-preserving patterns of VEVs of the \(\{\Phi_a\}\)-fields, suffice to naturally safeguard proton-longevity, to the extent needed, from all potential dangers, including those which may arise through gravity-induced higher dimensional operators \((d \geq 4)\) and the exchange of color-triplets in the infinite tower of heavy string states \[50\]. This protection holds in spite of the fact that certain \(\Phi_i\)'s acquiring VEVs carry \(| B - L | = 1\), which help provide superheavy Majorana masses to the RH neutrinos, but, in the process, break R-parity. The protection comes about because

\[7\] While \(U_1, U_2\) and \(U_3\) respectively assign the same charge to all 16 members of families 1,2 and 3, \(U_4, U_5\) and \(U_6\) distinguish between members within a family. Thus \(U_1, U_2\) and \(U_3\) commute with SO(10), but \(U_4, U_5\) and \(U_6\) do not.
the symmetries mentioned above prevent the appearance of the dangerous effective d=4 and d=5 operators, unless one utilizes non-renormalizable operators involving sufficiently high powers of the ratios $<\{\Phi_i\}>/M_{st}$, where each such ratio is naturally $O(1/10)$. These virtues of the extra flavor symmetries show that, believing in supersymmetry, superstring is suggested just to understand why the proton is so long-lived.

In above, I have tried to illustrate the beneficial role of string symmetries within one class of fairly realistic string solutions [47]. It still remains to be seen whether such string-symmetries by themselves can account for the desired suppression of the d=4 and the d=5 operators, regardless of the choice of the pattern of VEVs. [For attempts in this direction, see e.g. Ref. [53] and [54]].

I should add briefly that the string-flavor symmetries of the type just described are found to play a crucial role in resolving also some of the other problems of naturalness listed above. These include understanding the smallness of SUSY-breaking mass-splittings ($\delta m_s \sim 1$ TeV) on the one hand, and deriving the desired squark-degeneracy that adequately accounts for the suppression of the flavor-changing neutral current processes on the other hand. These two features are realized by implementing supersymmetry-breaking through a non-vanishing D-term of the string-derived anomalous U(1) gauge symmetry, noted above [55, 56]. The string-flavor symmetries also help in understanding the strong suppression of the neutrino-higgsino mixing mass [57] and the smallness of the CP violating part of the $K^0 - \bar{K}^0$ amplitude [58]. Last but not least, the same flavor symmetries help obtain the qualitatively correct pattern of hierarchical fermion masses and mixings [47]. Thus the beneficial roles of these string flavor symmetries can hardly be overemphasized.

One is of course aware that it is premature to take any specific string solution, or even a specific class of solutions, from the vast set of allowed ones, too seriously. Nevertheless it seems feasible that certain features, especially the symmetry properties, may well survive in the final picture that may emerge from the ultimate underlying theory, encompassing string theory, M theory and D-branes. These theories may of course well generate new symmetries in their strongly interacting phases which cannot be found in their weakly interacting versions. From a purely utilitarian point of view, given the magnitude of the naturalness problems, it seems that one way or another such flavor symmetries should in fact emerge from the underlying theory, just in order that supersymmetry would not conflict with the ideas of naturalness. Here, however, a bottom-up approach seems to be especially helpful in
providing insight into the nature of these flavor symmetries, that a satisfactory underlying theory needs to produce.

It needs to be mentioned that while the string-flavor symmetries provide the scope for obtaining a resolution of the problems mentioned above, obtaining a simultaneous resolution of all or most of them in the context of a given string solution is still a challenging task.

VE. A GUT or a Non-GUT String Solution?

In summary, comparing string-GUT with non-GUT solutions, where the former yield symmetries like SU(5) or SO(10), while the latter lead to symmetries like G(2113) or G(224), at the string scale, we see that each class has a certain advantage over the other. For a non-GUT solution, the gauge couplings unify only at the string-scale; thus one must assume that somehow a solution of the type discussed in Sec. 4 should resolve the mismatch between $M_X$ and $M_{st}$. This is plausible but not easy to ascertain. In this regard, a string GUT-solution yielding SU(5) or SO(10) appears to have an advantage over a non-GUT solution, because, in the case of the former, the couplings naturally stay together between $M_{st}$ and $M_X$. Furthermore, a GUT symmetry-breaking scale of $M_{st}/20$ seems to be plausible in the string-context.

On the other hand, as mentioned above, deriving a GUT-solution from strings, while achieving doublet-triplet splitting, is indeed a major burden, and has not been achieved as yet. In this regard, the non-GUT solutions seem to possess a distinct advantage, because the dangerous color-triplets are often naturally projected out [see e.g. 47, 48]. Furthermore, these solutions possess new symmetries, which are not available in GUTS, and some of these do not even commute with GUT-symmetries, but they do help in providing the desired protection, even against gravity-induced proton decay, that may otherwise be unacceptably rapid 50. In addition, as mentioned above, these new symmetries turn out to help in the resolution of the other naturalness-problems of supersymmetry as well (see e.g. Refs. 55, 57 and 58).

Weighing the advantages and possible disadvantages of both, it seems hard to make a clear choice between a GUT versus a non-GUT string-solution. While one may well have a preference for one over the other, it seems reasonable to keep one’s options open in this regard and look for other means, based e.g. on certain features of proton decay and the solutions to
the naturalness problems, which can help provide a distinction between the two alternatives. Short of making such a choice at this point, one must assume that for a GUT-solution, strings would somehow provide a resolution of the problem of doublet-triplet splitting, while for a non-GUT string-solution, it needs to be assumed that one of the mechanisms mentioned in Sec. 4 (for instance, that based on string-duality [32] and/or semi-perturbative unification [35]) is operative so as to remove the mismatch between $M_X$ and $M_{st}$.

I now discuss how the masses and the mixings of the fermions, especially those of the neutrinos, influence proton decay.

**VI. Link Between Neutrino Masses and Proton Decay**

Two important characteristics of supersymmetric unification, based on a gauge symmetry like SO(10) or a string-derived G(224), seem to be borne out by nature. They are: (a) gauge coupling unification at a scale $M_X \sim 2 \times 10^{16}$ GeV, and (b) light neutrino masses ($\ll m_{e,\mu,\tau}$). As discussed in Sec. 3, the value of $m(\nu_\tau) \approx 1/20$ eV, suggested by the SuperK result, is just about what one would expect within the symmetry-structure G(224)/SO(10), if the (B-L)–breaking scale is around $M_X$. One is thus naturally tempted to ask: Will proton decay — the other major prediction of grand unification — also reveal in the near future?

This question acquires a special significance because of the following circumstance. Ordinarily, except for the scale of new physics, involved in the two cases, proton decay, especially its decay modes are considered to be essentially unrelated to the pattern of neutrino masses. However, in a recent paper, Babu, Wilczek and I noted that neutrino masses can have a significant effect on proton decay as regards its rate as well as decay modes [59]. This is because in supersymmetric unified theories, based on SO(10) or G(224), assignment of heavy Majorana masses to the RH neutrinos (as discussed in Sec. 3), inevitably introduces a new set of color-triplets (unrelated to the electroweak doublets), whose effective couplings to quarks and leptons are related to these Majorana masses (see eqs. (4) and (5)). Exchange of these new color-triplets give rise to a new set of $d=5$ proton decay operators, which are thus directly related to the neutrino-masses. These are in addition to the standard $d=5$ operators which arise due to exchange of the familiar color-triplets that are related to the electroweak doublets (see Sec. 5). Even without the SuperK result on atmospheric-oscillation, assuming that $\nu_e - \nu_\mu$ oscillation is relevant to the MSW explanation of the solar neutrino puzzle,
so that $m(\nu_L^\mu) \approx 3 \times 10^{-3}$ eV, which corresponds to $M(\nu_R^\mu) \approx 2 \times 10^{12}$ GeV, the new $d=5$ operators by themselves (not including contributions from the standard $d=5$ operators) lead to proton lifetimes typically in the range: $\Gamma(p \to \nu K^+)_{\text{NewOp}}^{-1} \approx 10^{31.5 \pm 3}$ yrs. Now it could happen that the contributions from the standard $d=5$ operators are somehow suppressed. In particular, this would arise in the case of non-GUT string solutions leading to symmetries like $G(224)$ or $G(2113)$ for which the standard color-triplets get projected out through compactification [47, 48]. Even in this case, the new operators related to neutrino masses can still contribute to proton decay. As noted above, these lead to proton lifetimes in an interesting range which is accessible to SuperKamiokande searches.

Furthermore, the flavor-structure of the new $d=5$ operators are expected to be distinct from those of the standard $d=5$ operators, which are governed by the highly hierarchical Dirac masses of quarks and leptons. In contrast to the standard $d=5$ operators, the new ones can lead to prominent charged lepton decay modes, such as $\ell^+\pi^o$, $\ell^+K^o$ and $\ell^+\eta$, involving especially $\mu^+$, even for low or moderate values of $\tan\beta \leq 20$, together with $\bar{\nu}K^+$-modes. The intriguing feature thus is that owing to the underlying SO(10) or just SU(4)-color symmetry, proton decay operator knows about neutrino masses and vice versa.

SuperK result introduces new features to proton decay. With a maximal effective Majorana-coupling for the third family (i.e. $\lambda_{33} \sim O(1)$), as suggested in Sec.3, that corresponds to $M_{3R} \approx (\text{few} \times 10^{14}\text{GeV})$ for the case of no mixing (see eq. (5)), one might worry that proton would decay too fast, because of an enhancement in the new $d=5$ operators, relative to that considered in Ref. [59]. It turns out, however, that because $\tau^+$ is heavier than the proton and also because $\bar{\nu}_\tau K^+$ mode receives a strong suppression-factor from the small mixing angle associated with the third family ($V_{ub} \approx 0.002 - 0.005$), a maximal Majorana-coupling of the third family ($\lambda_{33} \sim O(1)$), that corresponds to $m(\nu_L^\tau) \approx (1/10 - 1/30)eV$, leads to dominant (or prominent) $\bar{\nu}_\tau K^+$-mode; but such a coupling is still compatible with present limit on proton lifetime [60].

Babu, Wilczek and I have recently attempted to understand the neutrino masses and mixings, as suggested by both the SuperKamiokande result (interpreted as $\nu_\mu - \nu_\tau$ oscillation) and the solar neutrino puzzle, within a predictive $SO(10)$ or $G(224)$-based quark-lepton unified description of the masses and mixings of all fermions—i.e. quarks, charged leptons as well as neutrinos [61]. Adopting familiar ideas of generating hierarchical eigenvalues through off-diagonal mixings and correspondingly Cabibbo-like mixing angles, we find that the bizarre
pattern of masses and mixings of quarks and charged leptons of all three families can in fact be described adequately (to better than 10% accuracy), within an economical SO(10)-framework, which makes five successful predictions, just for the quark and the charged lepton system.

In the process, the Dirac mass matrices of the neutrinos, as well as of the charged leptons, get fully determined. Taking the Dirac masses, thus fixed, together with a simple hierarchical pattern for the Majorana mass matrix of the superheavy right-handed neutrinos, we show that one can obtain quite naturally a large $\nu_\mu^L - \nu_\tau^L$ oscillation angle ($\sin^2 2\theta \simeq 0.85 - 0.95$), just as observed at SuperK, in spite of highly non-degenerate masses of the three light neutrinos—e.g. with $m(\nu_e^L) \ll m(\nu_\mu^L) \approx (1/10 - 1/20)m(\nu_\tau^L)$, where $m(\nu_\tau^L) \approx (1/20 \text{eV})(1/2 - 2)$. Such a hierarchical mass-pattern for the light neutrinos is of course natural to see-saw. In this case, $\nu_e - \nu_\mu$ oscillation becomes relevant to the small angle MSW explanation [61] of the solar neutrino puzzle [62]. The distinctive features of this explanation of the neutrino-anomalies are: (a) its origin within an underlying unified theory that relates the masses and mixings of neutrinos to those of quarks and charged leptons, and (b) the emergence of the large oscillation angle without a large mixing in either the $(\nu_\mu - \nu_\tau)$ or the $(\mu - \tau)$ mass-eigenstates.

As an important corollary to this work, owing to the link mentioned above between neutrino masses and proton decay [59], we find that the mass of $\nu_\tau$ and the large oscillation angle suggested by the SuperKamiokande result in fact imply a net enhancement in the proton decay rate, as well as of the $\mu^+K^0$ mode[60]. There are of course uncertainties in the prediction for proton-decay rate owing to uncertainties in the SUSY-spectrum, the hadronic matrix element and the relative phases of the many different contributions (see Ref. [60] for details). However, given that the individual contributions to the amplitude are enhanced by the neutrino and fermion mass-effects, and that there are several prominent channels (i.e. $\bar{\nu}_\tau K^+$, $\bar{\nu}_\mu K^+$ and $\mu^+K^0$), it seems that it would be hard to reconcile the ideas of supersymmetric unification described here, if the proton life-time exceeds about $10^{34}$ yrs [63]. Assuming such a unification, the prospect for discovery of proton decay at SuperK and/or at ICARUS thus seems strong.
To conclude, with neutrino masses and coupling unification revealed, proton decay remains as the missing link. Its discovery, with dominance of $\bar{\nu}K^+$ and prominence of $\mu^+K^0$ modes, would in fact be a double confirmation of both supersymmetric unification through $G(224)/SO(10)$, as well as of the ideas of neutrino masses, described above in this context.

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