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Links between neutrino oscillations, leptogenesis, and proton decay within supersymmetric grand unification*

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Abstract. Evidence in favor of supersymmetric grand unification including that based on the observed family multiplet-structure, gauge coupling unification, neutrino oscillations, baryogenesis, and certain intriguing features of quark–lepton masses and mixings is noted. It is argued that attempts to understand (a) the tiny neutrino masses (especially $\Delta m^2(\nu_2 - \nu_3)$), (b) the baryon asymmetry of the Universe (which seems to need leptogenesis), and (c) the observed features of fermion masses such as the ratio m_b/m_τ, the smallness of V_{cb} and the maximality of $\Theta^{\rm osc}_{\nu_\mu\nu_\tau}$, seem to select out the route to higher unification based on an effective string-unified $G(224) = SU(2)_{\rm L} \times SU(2)_{\rm R} \times SU(4)^{\rm c}$ or $SO(10)$-symmetry that should be operative in 4D, as opposed to other alternatives.

A predictive $SO(10)/G(224)$-framework possessing supersymmetry is presented that successfully describes the masses and mixings of all fermions including neutrinos. It also accounts for the observed baryon asymmetry of the Universe by utilizing the process of leptogenesis, which is natural to this framework. It is argued that a conservative upper limit on the proton lifetime within this $SO(10)/G(224)$-framework, which is so far most successful, is given by $(\frac{1}{3} - 2) \times 10^{34}$ years. This in turn strongly suggests that an improvement in the current sensitivity by a factor of five to ten (compared to SuperK) ought to reveal proton decay. Implications of this prediction for the next-generation nucleon decay and neutrino-detector are noted.

Keywords. Supersymmetry; proton decay; neutrino oscillation; leptogenesis.

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1. Introduction and an overview

Since the discoveries (confirmations) of the atmospheric [1] and solar neutrino oscillations [2,3], the neutrinos have emerged as being among the most effective probes

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into the nature of higher unification. Although almost the feeblest of all the entities of nature, simply by virtue of their tiny masses, they seem to possess a subtle clue to some of the deepest laws of nature pertaining to the unification scale as well as the nature of the unification symmetry. In this sense, the neutrinos provide us with a rare window to view physics at truly short distances. As we will see, these turn out to be as short as about 10^{-30} cm. Furthermore, it appears most likely that the origin of their tiny masses may be at the root of the origin of matter–antimatter asymmetry in the early Universe. In short, the neutrinos may well be crucial to our own origin!

The main purpose of my talk here today will be to present the intimate links that exist in the context of supersymmetric grand unification between the following phenomena: (i) neutrino oscillations, (ii) the masses and mixing of quarks and charged leptons, (iii) gauge coupling unification, (iv) baryogenesis via leptogenesis, and last but not the least (v) proton decay.

To set the background for a discussion along these lines, let us first recall that with only left-handed neutrinos, the standard model based on the gauge symmetry $SU(2)_{\rm L} \times U(1)_{\rm Y} \times SU(3)^{\rm c}$, despite its numerous successes, fails to account for the magnitude of the mass-difference square $\Delta m^2(\nu_2 - \nu_3) \sim (1/20 \text{ eV})^2$ observed at SuperKamiokande [1]. Incorporating effects of quantum gravity [3a], the standard model can lead to a neutrino masses of $\sim 10^{-5}$ eV, which is, however, too small to account for the SuperK effect. One can in fact argue that, to understand the magnitude of the SuperK effect in any natural way, one would need new physics beyond the standard model at an effective mass scale of $\sim 10^{15}$ GeV, rather than at the Plank scale of $\sim 10^{19}$ GeV [4]. Interestingly enough, one can link this effective mass scale to the scale of meeting of the three gauge couplings (to be discussed below) which is around 2×10^{16} GeV. That, in turn, hints at a link between the physics of neutrino oscillations and grand unification!

The idea of 'grand unification' was introduced in the early 1970s [5–7], purely on aesthetic grounds, in order to remove certain conceptual shortcomings of the standard model. Over the years, a set of key observations – some old and some new – have come to light, which together provide strong evidence in favor of this idea. Some of the observations in fact support the idea of both grand unification and low-energy supersymmetry [8,9]. The evidence includes:

(1) The observed family multiplet-structure – in particular the fact that the five (apparently disconnected) multiplets of the SM belonging to a family neatly become parts of a whole – a single multiplet – under grand unification, with all their quantum numbers predicted precisely as observed.

(2) The observed quantization of electric charge and the fact that the electron and the proton have exactly equal but opposite charges.

(3) The dramatic meeting of the three gauge couplings that is found to occur at a scale $M_X \approx 2 \times 10^{16}$ GeV, when they are extrapolated from their values measured at LEP to higher energies, in the context of supersymmetry [10].

(4) The tiny neutrino masses of the sort suggested by the discoveries/confirmations of atmospheric and solar neutrino oscillations. These, as we will see, not only go well with the scale of unification M_X mentioned above but also help select out a class of unification symmetries which provide the right-handed neutrinos ($\nu_{\rm R}'$s) as a compelling feature and $B - L$ as a local symmetry.

(5) Certain intriguing features of the masses and mixings of the quarks and leptons, including the relation $m_b(M_X) \approx m_\tau$ and the largeness of the $\nu_\mu - \nu_\tau$ oscillation angle ($\sin^2 2\theta^{\rm osc}_{\nu_\mu \nu_\tau} \geq 0.92$) together with the smallness of $V_{cb}(\approx 0.04)$ [11].

(6) And last but not the least, the likely need for leptogenesis [12,13] to account for the observed baryon asymmetry of the Universe, which seems to require once again the existence of superheavy right-handed neutrinos ($\nu'_{\rm R}$s) and $B-L$ as a local symmetry.

All these features including the tiny neutrino masses and the observed baryon asymmetry can be understood simply, and even quantitatively, within the concept of supersymmetric grand unification based on an effective symmetry in four dimensions, that is either [5]

$$G(224) = SU(2)_{\rm L} \times SU(2)_{\rm R} \times SU(4)^{\rm C}$$

or $SO(10)$ [14]. Believing in a unified theory of all forces including gravity, it is of course attractive to presume that such an effective symmetry in 4D ($G(224)$ or $SO(10)$) has its origin from a string theory or the M-theory. I have discussed elsewhere [15] that, in the context of a string theory with the string scale being close to the GUT scale, the observed coupling unification may be understood even if the effective symmetry in 4D, below the string scale, is non-simple like $G(224)$ [15a]. A string-derived $G(224)$ solution may, however, have an advantage over an $SO(10)$ solution in that it can neatly avoid the so-called doublet–triplet splitting problem (generic to SUSY GUTs) [15]. Motivated by the desire to avoid this problem, there have in fact been several attempts in the literature (many rather recent) which successfully obtain semi-realistic $G(224)$ solutions in 4D from compactification of a string theory [16], or of an effective five- or six-dimensional GUT theory [17]. For most purposes, in particular for considerations of fermion masses, neutrino oscillations, and leptogenesis, the symmetries $G(224)$ and $SO(10)$ provide essentially the same advantages.

Let us first recall the new features (relative to the SM) which are introduced through the symmetry $G(224)$ [5]. Subject to left–right discrete symmetry (L↔R), which is natural to $G(224)$, all members of the electron family become parts of a single left–right self-conjugate multiplet, consisting of

$$F^e_{\rm L,R} = \begin{bmatrix} u_r & u_y & u_b & \nu_e \\ d_r & d_y & d_b & e^- \end{bmatrix}_{\rm L,R} . \tag{1}$$

The multiplets $F^e_{\rm L}$ and $F^e_{\rm R}$ are left–right conjugates of each other and transform respectively as (2,1,4) and (1,2,4) of $G(224)$; likewise for the muon and the tau families. The symmetry $SU(2)_{\rm L}$ treats each column of $F^e_{\rm L}$ as a doublet; likewise $SU(2)_{\rm R}$ for $F^e_{\rm R}$. The symmetry $SU(4)$-color unifies quarks and lepotons by treating each row of $F^e_{\rm L}$ and $F^e_{\rm R}$ as a quartet; thus lepton number is treated as the fourth color. As mentioned above, because of the parallelism between $SU(2)_{\rm L}$ and $SU(2)_{\rm R}$, the symmetry $G(224)$ naturally permits the notion that the fundamental laws of nature possess a left ↔ right discrete symmetry (i.e. parity invariance) that interchanges $F^e_{\rm L} \leftrightarrow F^e_{\rm R}$ and $W_{\rm L} \leftrightarrow W_{\rm R}$. With suitable requirements on the Higgs sector, observed parity violation can be attributed, in this case, entirely to a spontaneous breaking of the L ↔ R discrete symmetry [18].

Furthermore, the symmetry $G(224)$ introduces an elegant charge formula: $Q_{\mathrm{em}} = I_{3\mathrm{L}} + I_{3\mathrm{R}} + (B-L)/2$, that applies to all forms of matter (including quarks and leptons of all six flavors, Higgs and gauge bosons). Note that the weak hypercharge of the standard model, given by $Y_W = I_{3\mathrm{R}} + (B-L)/2$, is now completely determined for all members of a family. Quite clearly, the charges $I_{3\mathrm{L}}$, $I_{3\mathrm{R}}$, and $B-L$, being generators respectively of $SU(2)_{\mathrm{L}}$, $SU(2)_{\mathrm{R}}$, and $SU(4)^{\mathrm{c}}$, are quantized; so also then is the electric charge Q_{em}. Using the expression for Q_{em}, one can now explain why the electron and the proton have exactly equal but opposite charges.

Note also that postulating either $SU(4)$-color or $SU(2)_{\mathrm{R}}$ forces one to introduce a right-handed neutrino (ν_{R}) for each family as a singlet of the SM symmetry. This requires that there should be sixteen two-component fermions in each family, as opposed to fifteen for the SM. Furthermore, $SU(4)$-color possesses $B-L$ as one of its generators. This in turn helps to protect the Majorana masses of the right-handed neutrinos from being of the order string or Planck scale [18a]. In addition, $SU(4)$-color provides the Dirac mass of the tau-neutrino by relating it to the top-quark mass at the unification scale, and simultaneously the mass of the bottom quark in terms of that of the tau-lepton. In short, $SU(4)$-color introduces three characteristic features, i.e.,

(1) the right-handed neutrinos as a compelling feature,
(2) $B-L$ as a local symmetry, and
(3) the two GUT scale mass relations:

$$m_b(M_X) \approx m_\tau \quad \text{and} \quad m(\nu^\tau_{\mathrm{Dirac}}) \approx m_{\mathrm{top}}(M_X). \tag{2}$$

These two relations arise from the $SU(4)$-color preserving leading entries in the fermion mass matrices which contribute to the masses of the third family [11]. The sub-leading corrections to the fermion mass matrices that arise from $SU(4)$-color breaking in the $(B-L)$ direction turn out to be important for the masses and mixings of the fermions belonging to the first two families [11]. These three ingredients, as well as the SUSY unification scale M_X, turn out to play crucial roles in providing us with an understanding of the tiny masses of the neutrinos as well as the baryon asymmetry of the Universe, by utilizing respectively the see-saw mechanism [19] and the idea of leptogenesis [12]. The success of the predictions in this regard (see below), speaks in favor of the see-saw mechanism and suggests that the effective symmetry in 4D, below the string scale, should contain $SU(4)$-color.

Now the minimal symmetry containing $SU(4)$-color on the one hand and also possessing a rationale for the quantization of electric charge on the other hand is provided by the group $G(224)$. The group $G(224)$ being isomorphic to $SO(4)\times SO(6)$ embeds nicely into the simple group $SO(10)$. The group $SO(10)$, which historically was proposed after the suggestion of $G(224)$, of course retains all the advantages of $G(224)$, in particular the features (a)–(c) listed above. The interesting point is that $SO(10)$ even preserves the 16-plet multiplet structure of $G(224)$ by putting $\{F_{\mathrm{L}} + (F_{\mathrm{R}})^{\mathrm{c}}\}$ as its spinorial 16-dimensional representation, thereby avoiding the need for any new matter fermions. By contrast, if one extends $G(224)$ to the still higher symmetry E_6 [20], one must extend the family structure from a 16- to a 27-plet, by postulating additional fermions.

Now utilizing the three ingredients (1), (2), and (3) listed above (thus assuming that $SU(4)$ color holds in 4D near the GUT scale), together with the SUSY unification scale (M_X) and the see-saw mechanism, one arrives at a set of predictions which include [11]:

$$\begin{aligned}
&m_b(m_b) \approx 4.7\text{–}4.9\ \text{GeV},\\
&m(\nu_3) \approx \left(\frac{1}{24}\ \text{eV}\right)\left(\frac{1}{2}-2\right),\\
&\sin^2 2\theta^{\text{osc}}_{\nu_\mu\nu_\tau} \approx 0.99,\\
&V_{cb} \approx 0.044,\\
&V_{us} \approx 0.20,\\
&|V_{ub}| \approx 0.003,\\
&m_d(1\ \text{GeV}) \approx 8\ \text{MeV}.
\end{aligned} \tag{3}$$

Each of these predictions agrees remarkably well with observations. The most intriguing feature is that this framework provides a compelling reason for why V_{cb} is so small ($\approx$0.04), and simultaneously why $\sin^2 2\theta_{\nu_\mu\nu_\tau}$ is so large ($\approx$1), both in accord with observations. It is worth noting that the last two results, showing a sharp difference between V_{cb} and $\theta_{\nu_\mu\nu_\tau}$, go against the often expressed (naive) view that the quark–lepton unification should lead to similar mixing angles in the quark and lepton sectors. Quite to the contrary, the minimal Higgs system provides a natural breaking of $SU(4)$-color along the $(B-L)$ direction which particularly contributes to a mixing between the second and the third families [11]. That in turn provides a compelling group-theoretical reason for a distinction between the masses and mixings of the quarks and leptons as in fact observed empirically.

One important consequence of having an effective $G(224)$ or $SO(10)$-symmetry in 4D is that spontaneous breaking of such a symmetry (thereby of $B-L$) into the SM symmetry naturally generates Majorana masses of the RH neutrinos that are of order GUT scale or smaller. In correlation with the flavor symmetries which provide the hierarchical masses of the quarks and the leptons, the Majorana masses of the three RH neutrinos are found to be [21]: $(M_{N_1}, M_{N_2}, M_{N_3}) \approx (10^{15}, 2\times 10^{12}, (1/3-2)\times 10^{10})$ GeV. Given lepton number (thus of $B-L$) violation associated with these Majorana masses, and C and CP-violating phases that generically arise in the Dirac and/or Majorana mass matrices, the out-of-equilibrium decays of the lightest of these heavy RH neutrinos (produced after inflation [21a]) into $l+H$ and $\bar{l}+\bar{H}$, and the corresponding SUSY modes, generates a lepton asymmetry. The latter is then converted into a baryon asymmetry by the electroweak sphaleron process [12,13]. In conjunction with an understanding of the fermion masses and neutrino oscillations (atmospheric and solar), the baryon excess thus generated is found to be [21]:

$$Y_B = \left(\frac{n_B - n_{\bar{B}}}{n_s}\right) \approx (\sin 2\phi_{21})(7\text{–}100)\times 10^{-11}. \tag{4}$$

While the relevant phase angle ϕ_{21} arising from C and CP-violating phases in the Dirac and Majorana mass matrices of the neutrinos is not predictable within the framework, it is rather impressive that for plausible and natural values of the phase angle $\phi_{21} \approx \frac{1}{2} - \frac{1}{20}$ (say), the calculated baryon excess Y_B agrees with the observed value based on big bang nucleosynthesis [22] and CMB data [23]. This may be contrasted from many alternative mechanisms, such as GUT and electroweak baryogenesis, which are either completely ineffective (owing to inflation and gravitino constraint) or yield too small a baryon excess even for a maximal phase. For a recent review and other relevant references on the topic of baryogenesis, see [24].

It should be stressed that the five predictions shown in eqs (3) and (4), together make a crucial use of the three features (a)–(c) listed in eq. (2), as well as the SUSY unification scale M_X and the see-saw mechanism. Now the properties (a)–(c) are the distinguishing features of the symmetry $G(224)$. They are of course available within any symmetry that contains $G(224)$ as a subgroup. Thus they are present in $SO(10)$ and E_6, though not in $SU(5)$. Effective symmetries like $[SU(3)]^3$ [25] or $SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_{B-L} \times SU(3)^{\mathrm{c}}$ [26] possess the first two features (a) and (b) but not (c). Flipped $SU(5) \times U(1)$ [27] on the other hand offers (a) and (b) but not the relation $m_b(M_X) \approx m_\tau$, which, however, is favored empirically.

The empirical success of the features (1)–(6), including specifically the predictions listed in eqs (3) and (4), seems to be non-trivial. Together they make a strong case for both the conventional ideas of supersymmetric grand unification and simultaneously for the symmetry $G(224)$ or $SO(10)$ being relevant to nature in four dimensions, just below the string scale.

As mentioned before, the main purpose of my talk here will be to present the intimate links that exist, in the context of supersymmetric grand unification based on an effective $G(224)$ or $SO(10)$ symmetry, between (i) neutrino oscillations, (ii) the masses and mixings of quarks and charged leptons, (iii) gauge coupling unification, (iv) baryogenesis via leptogenesis, and last but not the least (v) proton decay.

Perhaps the most dramatic prediction of grand unification is proton decay. This important process which would provide the window to view physics at truly short distance ($<10^{-30}$ cm) and would greatly complement studies of neutrino oscillations in this regard is yet to be seen. I have discussed in a recent review [28] in some detail the updated results for proton decay in the context of supersymmetric $SU(5)$, $SO(10)$ and $G(224)$ symmetries by taking into account (a) the recently improved (and enhanced) matrix elements as well as short and long-distance renormalization effects, (b) the dependence of the 'standard' $d = 5$ proton-decay operator on GUT-scale threshold corrections that are restricted by the requirement of natural coupling unification, and (c) its link with the masses and the mixings of all fermions including neutrinos [11]. The latter give rise to a new set of $d = 5$ operators, related to the Majorana masses of the RH neutrinos [29], which are found to be important. Following these considerations, one can argue that the evidence listed above in favor of supersymmetric grand unification, based on an effective $G(224)$ or $SO(10)$ symmetry in 4D, strongly suggests that an upper limit on proton lifetime is given by

$$\tau_{\text{proton}} \lesssim \left(\frac{1}{3} - 2\right) \times 10^{34}\ \text{yr},$$

with $\bar{\nu}K^+$ being the dominant mode, and quite possibly μ^+K^0 and $e^+\pi^0$ being prominent. This in turn suggests that an improvement in the current sensitivity by a factor of five to ten (relative to SuperK) ought to reveal proton decay. A next-generation megaton-size detector of the kind being contemplated by the UNO [30] and the HyperKamiokande [31] proposals would thus be needed to probe efficiently into the prediction of the supersymmetric $G(224)/SO(10)$-framework as regards proton decay.

2. Concluding remarks

In this talk, I have argued that but for two missing pieces – supersymmetry and proton decay – the evidence in favor of supersymmetric grand unification is now strong. It includes: (i) the observed family multiplet-structure, (ii) quantization of electric charge, (iii) the meeting of the three gauge couplings, (iv) neutrino oscillations (atmospheric and solar), (v) the intricate pattern of the masses and mixings of all fermions, including neutrinos, and (vi) the likely need for leptogenesis to account for the observed baryon asymmetry of the Universe. All of these features can be understood simply and even quantitatively (see eqs (3) and (4)) within the concept of supersymmetric grand unification based on an effective string-unified $G(224)$ or $SO(10)$ symmetry in 4D. Attempts to understand especially (a) the tiny neutrino masses, (b) the baryon asymmetry of the Universe (via leptogenesis), as well as (c) certain features of quark–lepton masses and mixings seem to select out the $G(224)/SO(10)$ route to unification, as opposed to other alternatives.

A systematic study of proton decay has thus been carried out within this $SO(10)/G(224)$ framework [11,28], allowing for the possibilities of both MSSM and ESSM, and including the contributions for the gauge boson-mediated $d = 6$, the standard $d = 5$ as well as the new $d = 5$ operators related to the Majorana masses of the RH neutrinos. Based on this study, I have argued that a conservative upper limit on the lifetime of the proton is about $(\frac{1}{3}\text{–}2) \times 10^{34}$ years.

So, unless the fitting of all the pieces (i)–(vi) listed above is a mere coincidence (it is hard to believe that that is the case) discovery of proton decay should be around the corner. Allowing for the possibility that proton lifetime may well be near the upper limit stated above, a next generation detector, of the type proposed by UNO and HyperKamiokande, providing a net gain in sensitivity by about a factor of five to ten, compared to SuperK, would thus be needed to produce real proton decay events and distinguish them from the background.

The reason for pleading for such improved searches is that proton decay would provide us with a wealth of knowledge about physics at truly short distances ($< 10^{-30}$ cm), which cannot be gained by any other means. Specifically, the observation of proton decay, at a rate suggested above, with $\overline{\nu}K^+$ mode being dominant, would not only reveal the underlying unity of quarks and leptons but also the relevance of supersymmetry. It would also confirm a unification of the fundamental forces at a scale of order 2×10^{16} GeV. Furthermore, prominence of the μ^+K^0 mode, if seen, would have even deeper significance, in that in addition to supporting the three features mentioned above, it would also reveal the link between neutrino masses and proton decay, as discussed in §5 (refer archives). In this sense, the role of proton decay in probing into physics at the most fundamental level is unique. In view of how valuable such a probe would be and the fact that the predicted upper limit on the proton lifetime is at most a factor of three to ten higher than the empirical lower limit, the argument in favor of building an improved detector seems compelling.

Such a detector should of course be designed to serve multiple goals including especially improved studies of neutrino oscillations and supernova signals. These ideas and others including that of a neutrino factory were discussed intensively at the NeSS meeting held recently in Washington [32].

To conclude, the discovery of proton decay would constitute a landmark in the history of physics. That of supersymmetry would do the same. The discoveries of these two features – supersymmetry and proton decay – would fill the two missing pieces of gauge unification and would shed light on how such a unification may be extended to include gravity in the context of a deeper theory. The question thus poses: Will our generation give itself a chance to realize *both*?

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thereby to too small a value for Δm^2_{23} compared to observation. Hence the need for $B-L$ as an effective local symmetry in 4D near the string scale

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