Beyond The Standard Model Physics: Grand Unification & Otherwise

A THESIS

submitted for the Award of Ph.D. degree of

MOHANLAL SUKHADIA UNIVERSITY

BY

Ketankumar Patel

FACULTY OF SCIENCE

MOHANLAL SUKHADIA UNIVERSITY

UDAIPUR

Year of submission: 2011

There is a fine line between wrong & visionary.
Unfortunately, one has to be a visionary to see it.

Dr. Sheldon Cooper (*fictitious character*)
[The Big Bang Theory: Season 3, Episode 04]

DECLARATION

I **Mr. Ketankumar Patel**, S/o Mr. Mohanbhai Patel, resident of C/426, Vivekanand nagar society, Maninagar, Ahmedabad 380 008, hereby declare that the research work incorporated in the present thesis entitled, **"Beyond The Standard Model Physics: Grand Unification & Otherwise"** is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I have properly acknowledged the material collected from secondary sources wherever required. I solely own the responsibility for the originality of the entire content.

Date:

Ketankumar Patel

(Author)

CERTIFICATE

I feel great pleasure in certifying that the thesis entitled, **"Beyond The Standard Model Physics: Grand Unification & Otherwise"** by Mr. Ketankumar Patel under my guidance. He has completed the following requirements as per Ph.D regulations of the University.

(a) Course work as per the university rules.

(b) Residential requirements of the university.

(c) Regularly submitted six monthly progress reports.

(d) Presented his work in the departmental committee.

(e) Published minimum of one research papers in a referred research journal.

I recommend the submission of thesis.

Date:

Dr. Namit Mahajan
(Thesis Supervisor)
Reader, Theoretical Physics Division,
Physical Research Laboratory,
Ahmedabad - 380 009.

Countersigned by

Head of the Department

ACKNOWLEDGEMENTS

The work reported in this thesis has been carried out under the guidance of Prof. Anjan Joshipura. I express my most sincere and deep gratitude to him for his invaluable guidance, encouragement and support throughout the course of this work. I am immensely benefited from his insight and expertise in the subject. His enthusiasm, kind nature and positive outlook have made the years working with him pleasant and memorable. I consider myself very fortunate to have been able to work with him. I am very grateful to my thesis supervisor Dr. Namit Mahajan who has always helped me in several problems whenever I approached him. I thank him for his continuous encouragement, concerns, and very useful advises. His helps in physics and administrative formalities and his dedicated efforts in upgrading the computer facilities in the division have made my work very easy and enjoyable.

I would like to thank my collaborators Sudhir Vempati, Bhavik Kodrani, Pankaj Sharma, Stefano Morisi and Eduardo Peinado for providing me opportunities to work with them. Working with all of them was a great learning experience in my career. Especially, sharing ideas with Bhavik and Pankaj has provided me a good insight of the subject and has cleared many of my doubts. I also thank Prof. Jose Valle for arranging my visit to University of Valencia in Spain which gave me an opportunity to interact and work with his group members.

I warmly thank: Prof. Saurabh Rindani for useful comments, Prof. Utpal Sarkar for motivating me to pursue my career in high energy physics, Prof. Subhendra Mohanty, Dr. Dilip K. Ghosh, Dr. Srubabati Goswami, Dr. R. Rangarajan, Prof. P. K. Panigrahi and Dr. Dilip K. Angom for teaching useful courses, Santosh K. Singh for helping me in learning Group Theory, Bhavik for teaching me the software packages for the numerical optimization and perhaps more importantly for helping me to understand how PRL administration works, Pankaj for several useful discussions on the subject and for clarifying my doubts, Vimal for making things difficult to understand, Arvind Singh for helping me in understanding Vimal's concepts, Vineet for setting up brain teasers in lunch and tea breaks, Amzad for listening me and Vineet patiently, Suman for helping me whenever I got stuck in Linux operations, Bhaswar and Pravin for being nice companions during several trips to Udaipur, my batch mates JRF-07 for making coursework enjoyable and some of my senior and younger colleagues for sharing some memorable time with me in PRL.

The kind of support, encouragement, love, care and conducive environment that I have been receiving from my parents since I was born are something beyond acknowledgements. I must thank my younger sister for making me little organized. Finally, I am indebted to Manisha for her immense understanding and being actively involved in family even though staying away from us.

Ketan M. Patel

ABSTRACT

Grand unified theories (GUTs) which unify strong and electroweak interactions also provide a constrained and unified description of all the fermions. In particular, the renormalizable versions of GUTs based on $SO(10)$ gauge group are considered as excellent platforms to study the peculiar patterns of quark and lepton masses and mixing angles observed in nature. In this thesis, we examine many such $SO(10)$ models for their viability or otherwise in explaining all the fermion masses and mixing angles. The different $SO(10)$ models, which we study in this work, can be divided in three main categories: (i) the supersymmetric $SO(10)$ models (ii) the sypersymmetric $SO(10)$ models with flavor symmetries and (iii) the non-supersymmetric $SO(10)$ models.

First we carry out an exhaustive analysis of supersymmetric models with minimal ($10_H + \overline{126}_H$) and non-minimal ($10_H + \overline{126}_H + 120_H$) Higgs content. Extensive numerical fits to fermion masses and mixing are carried out in each case assuming dominance of type-II or type-I seesaw mechanism. We use data corresponding to different values of $\tan\beta$ and with or without appreciable finite supersymmetric threshold corrections. All the cases studied provide quite good fits if the type-I seesaw mechanism dominates. This is not the case in the minimal model based on several data sets and type-II seesaw mechanism. This can be traced to the absence of the b-τ unification at the GUT scale in these cases. In contrast, the type-II seesaw mechanism works uniformly well in all the non-minimal model. Required scale of the $B - L$ breaking is identified in each case. In the case of type-I seesaw dominance in both the minimal and non-minimal models, it is observed that the $B-L$ breaking scale inferred from neutrino masses lies closer to the GUT scale compared to the type-II seesaw mechanism.

In $SO(10)$ models, it is not clear if the exact tribimaximal mixing (TBM) among leptons would be consistent with a precise description of the quark masses and mixing. We address this question by developing a novel formalism which allows determination of most general structures of the neutrino and charged lepton mixing matrices consistent with tribimaximal mixing. These

are then integrated into an $SO(10)$ model within which detailed fits to fermion masses and mixing angles are given. It is shown that one can obtain excellent fits to all the fermion masses and quark mixing angles keeping tri-bimaximal leptonic mixing intact. Various perturbations to tri-bimaximal mixing which can arise in the model are considered and their impact on the predictions of the reactor mixing angle θ_{13} is numerically discussed.

In the second part of this thesis, we study some interesting consequences of different flavor symmetries when integrated with supersymmetric $SO(10)$ frameworks. First we integrate the μ-τ symmetry in the non-minimal supersymmetric $SO(10)$ model. This scenario is shown to lead to a generalized CP invariance of the mass matrices and vanishing CP violating phases if the Yukawa couplings are invariant under the μ-τ symmetry. Small explicit breaking of the μ-τ symmetry is then shown to provide a very good understanding of all the fermion masses and mixing. Second we propose a specific ansatz for the structure of Yukawa matrices in $SO(10)$ models which differ from its generic expectations of hierarchical neutrinos and lead to quasi degenerate neutrino masses through the type-I seesaw mechanism. Consistency of this ansatz is demonstrated through a detailed fits to fermion masses and mixing angles all of which can be explained with reasonable accuracy in a model which uses the most general Yukawa Higgs sector of $SO(10)$. The proposed ansatz is shown to follow from an extended model based on the three generations of the vector like fermions and an $O(3)$ flavour symmetry. Large neutrino mixing angles emerge as a consequence of neutrino mass degeneracy in this model. In the last section in this category, we propose a discrete symmetry $S_4 \times Z_n$ when suitably integrated with $SO(10)$ provides a viable framework to obtain an interesting empirical relation called Quark-Lepton Complementarity (QLC), namely $\theta_{12}^l \sim \pi/4 - \theta_C$. Consistency of this model is discussed through detailed analysis of fermion masses and mixing angles. The model leads to the lepton mixing matrix that is dominantly bimaximal with $\mathcal{O}(\theta_C)$ corrections related to quark mixings which generically predicts the large reactor angle $\theta_{13}^l \sim \theta_C/\sqrt{2}$.

In the last part of this thesis, we carry out a detailed study of some non-

supersymmetric $SO(10)$ models. The non-supersymmetric $SO(10)$ models with a global $U(1)_{PQ}$ symmetry lead to the similar Yukawa sum-rules predicted in the supersymmetric models. Detailed numerical fits to fermion masses and mixing are carried out in each case assuming dominance of type-II or type-I seesaw mechanism. It is shown that the minimal non-supersymmetric model with type-I seesaw dominance gives excellent fits. In the presence of a 45_H and an intermediate scale, the model can also account for the gauge coupling unification making it potentially interesting model for the complete unification. Structure of the Yukawa coupling matrices obtained numerically in this specific case is shown to follow from a very simple $U(1)$ symmetry and a Froggatt-Nielsen singlet. The non-minimal model with type-I seesaw also provides an excellent fit to entire fermion spectrum while the model with $120_H + \overline{126}_H$ fails badly in this task. It is observed that type-II seesaw dominance is disfavored in all the models because of non-unification of b quark and τ masses at the GUT scale in the absence of supersymmetry.