Synopsis

The standard model of particle physics, though immensely successful in terms of experimental agreement, leaves many questions unanswered. Not the least of which is the problem of fermion masses which are not predicted by the minimal model and are only phenomenologically determined. In principle, a study of this problem can enlighten us about the possible extensions of the standard model that could resolve many of the puzzling issues. In the case of the quark masses and mixings, various aesthetic but partial solutions have been offered. These involve imposing on the quark mass matrices different ansätze motivated by particular models with higher gauge symmetry and/or experimental observations. With neutrinos the situation is even more fluid. While there is hardly any direct evidence for nonzero neutrino masses, yet the potentially rich phenomenology and the dramatic consequences in astrophysical and terrestrial laboratories that their existence would imply has spurred many studies.

The present thesis is divided into two distinct but connected parts that look at some of the questions raised above. The first part deals with the study of quark mass matrices. The most popular ansätze discussed in the literature are those due to Stech and Fritzsch and certain modifications thereof and are examined here for concurrence with constraints coming from three sets of experimental observations. These are the measurement of ϵ_K, the parameter describing the indirect CP violation in the neutral K–system or, in other words, the CP violation in interactions changing strangeness by two units ($\Delta S = 2$), and the more recent measurements of the B_d^0–$\overline{B_d^0}$ mixing parameter x_d (which gives the time–integrated probability of a $\overline{B_d^0}$ appearing in a B_d^0 beam) and the direct ($\Delta S = 1$) CP violation parameter ϵ'_K, *i.e.* the one relevant in K–decays. It is found that while the Stech ansatz can be made consistent with ϵ_K and x_d for low top quark mass ($m_t \sim 45 GeV$, an experimentally consistent value when the work was done but ruled out since) it is completely ruled out by ϵ'_K/ϵ_K [35]. As a corollary, all schemes incorporating the Stech assumptions are proved to be inconsistent. On the other hand the Fritzsch and other Fritzsch-like schemes still do admit many solutions (albeit with a much restricted parameter space) but with different characteristics for different ranges of m_t [35].

These observations naturally led to a model independent analysis of the most general quark mass matrices for three families [38]. It was shown how phenomenological considerations restrict the parameter space to different disjoint sectors. The constraints on the general form that lead to various ansätze were examined and it was shown that all the popular models lie in a particular one of the aforementioned sectors [38]. The analysis also points out the alternative directions future model–building efforts could adopt.

The second part of the thesis deals with the problem of neutrino masses and some related topics. The relation between the Majorana masses of the neutrinos and neutrinoless double beta decay [$(\beta\beta)_{0\nu}$] was reexamined and it was argued that, contrary to naive expectations, the $(\beta\beta)_{0\nu}$ rate does not distinguish between the Dirac and Majorana mass of the physical electron neutrino (ν_e) [53]. It had been held that if the tritium β–decay experiments indicate a neutrino mass larger than that predicted by $(\beta\beta)_{0\nu}$, then ν_e has to be a Dirac particle and models were constructed to incorporate such an eventuality. Based on our analysis, we propose a new scenario wherein the physical ν_e can naturally be a Majorana neutrino without any $(\beta\beta)_{0\nu}$. Some supersymmetric grand unified theories were shown to yield such scenarios naturally [53]. These models turn out to be much simpler and more economical than existing ones predicting light Dirac neutrinos.

A related question is that of the neutrino magnetic moments, a large value of which would offer a solution to the solar neutrino problem (the longstanding discrepancy between the ν_e absorption rates in the Davis experiment and that predicted by the standard solar model) and has the added advantage of explaining the apparent anticorrelation between the solar neutrino flux and the sunspot activity. A model – based on a gauged $SO(3)$ horizontal symmetry – that decouples the magnetic transition moment of the neutrino from its Majorana mass was constructed, thus allowing large magnetic moments for nearly massless neutrinos [66]. The present scheme is most strikingly different from all the others of its genre in that not only does it not depend upon an intact $SU(2)_\nu$ symmetry between neutrinos to suppress their mass while allowing a large magnetic moment (Voloshin mechanism), rather in this case the appearance of the last–mentioned actually hinges on the breaking of the symmetry in question. The model, while treating all fermions on par, also avoids observable Goldstone bosons, excessive fine tuning and extra fermions, embarassments which plagued earlier efforts.

We next study the problem of the gravitational helicity flip of a massive neutrino. If the neutrinos be massive, then interactions that flip their helicities could have dramatic implications for the cooling of hot neutron matter during stellar collapse. With a central core as massive and compact as a neutron star, gravitational helicity flip could play an important role too. A semiclassical analysis of the gravitational scattering problem for low energy neutrinos in the vicinity of a neutron star shows that this mechanism could in fact overwhelm all other known sources of helicity flip! From a study of cooling rates of the supernova SN 1987A, strong bounds were placed on parity violating gravitational interaction strengths [74].

Finally, we integrate the aforementioned ideas in neutrino physics in the quest of a natural model for the recently reported 17 keV neutrino. In the $SU(2)_H$ model that is constructed for the purpose, the required mass scale $\sim O(100\, keV - 1\, MeV)$ is generated radiatively. The crippled see–saw mechanism then naturally leads to a pseudo–Dirac ν_τ that is identified with the new find. This particle can hence be used as a very good probe for gravitational helicity flips. The Majorana neutrinos ν_e and ν_μ remain extremely light (mass $\sim O(10^{-5} - 10^{-4}\, eV)$) but possess a relatively large transition magnetic moment $\mu_{\nu_e\nu_\mu} \sim 10^{-12}\mu_B$. The $(\beta\beta)_{0\nu}$amplitude is extremely small and is consistent with all bounds. The spontaneous lepton number violation in the theory results in a $SU(2)_L$ singlet–doublet Majoron unconstrained either by the LEP results on the Z–decay width or the astrophysical bounds. The ν_τ in the model is very short-lived and primarily decays into ν_μ and the Majoron.

To summarise, during the course of this work we have looked at various aspects of fermion masses and mixings and examined some of their observable consequences. On the hadronic front, certain well–discussed forms for the quark mass matrices were examined in the context of new experimental results, either to rule them out or to severely curtail the limits of their validity. A general model–independent analysis of the problem provides insights into the assumptions involved in the existing models and brings into perspective the course future model–building should adopt. In the leptonic sector, the study of neutrino masses exhibited the independence of the $(\beta\beta)_{0\nu}$ rate and the Majorana or Dirac mass of the ν_e. An economical model that naturally led to light Majorana neutrinos with no $(\beta\beta)_{0\nu}$ was constructed. A novel mechanism was also proposed to generate large magnetic moments for neutrinos while keeping their masses small. The scheme avoided the pitfalls faced by earlier efforts in this direction. An examination of astrophysical consequences of a non–zero neutrino mass exhibited the dominance of gravitational effects in the helicity flipping transitions of low energy neutrinos in the vicinity of a massive dense object. This also led to imposition of a very strict bound on possible parity–violating effects in gravity. Last but not the least, a model that can naturally accomodate the exciting new find of a 17 keV neutrino as well as a relatively large $\mu_{\nu_e\nu_\mu}$ is presented. As phenomenological viability demands consistency of the predictions for neutrino oscillation and $(\beta\beta)_{0\nu}$ rates with the experimental bounds, this study brings into focus the interrelationships of all the issues in neutrino physics discussed here.