Schemes for Neutrino Mass and Mixing

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Abstract

I briefly review various schemes of neutrino mass generation which are motivated by present experimental hints from solar and atmospheric neutrinos as well as cosmological data on the amplitude of primordial density fluctuations.

1. Preliminaries

Neutrinos are the only apparently massless electrically neutral fermions in the standard model and the only ones without right-handed partners. It is rather mysterious that they seem to be so special when compared with the other fundamental fermions. Indeed, having no electric charge, a Majorana mass term for neutrinos may arise even in the absence of right-handed components. On the other hand, many unified extensions of the standard model, such as SO(10), do require the presence of right-handed neutrinos in order to realize the extra symmetry. Either way one expects neutrinos to be massive. Moreover, there is, in these theories, a natural mechanism, called seesaw, to understand the relative smallness of neutrino masses [1, 2]. In general the seesaw mechanism provides just a general scheme, rather than detailed predictions. These will depend, among other factors, upon the structure not only of the Dirac type entries, but also on the possible texture of the large Majorana mass term [3].

Although attractive, the seesaw mechanism is by no means the only way to generate neutrino masses. There are many other attractive possibilities, some of which do not require any new large mass scale. The extra particles required to generate the neutrino masses have masses at scales accessible to present experiments [4].

It is also quite plausible that B-L or lepton number, instead of being part of the gauge symmetry [5] may be a spontaneously broken global symmetry. The scale at which such a symmetry gets broken does not need to be very high, as in the original proposal [6], but can be rather low, close to the weak scale [7]. Such a low scale for lepton number breaking could have important implications not only in astrophysics and cosmology but also in particle physics.

Unfortunately, present theory is not capable of predicting the scale of neutrino masses any better than it can fix the masses of the other fermions, say the muon. One should at this point turn to experiment.

There are several limits on neutrino masses that follow from observation. The laboratory bounds may be summarized as

\[ m_{\nu_e} \lesssim 5 \text{ eV}, \quad m_{\nu_\mu} \lesssim 250 \text{ keV}, \quad m_{\nu_\tau} \lesssim 31 \text{ MeV} \]  \hspace{1cm} (1)

and follow purely from kinematics. These are the most model-independent of the neutrino mass limits. The improved limit on the \( \nu_e \) mass was given by Lobashev at this conference [8], while that on the \( \nu_\tau \) mass may be substantially improved at a future tau factory [9].

In addition, there are limits on neutrino masses that follow from the nonobservation of neutrino oscillations [10], which involve neutrino mass differences versus mixing, and disappear in the limit of unmixed neutrinos.
Another important limit arises from the non-observation of $\beta\beta_0$ decay, i.e. the process by which nucleus $(A, Z - 2)$ decays to $(A, Z) + 2 e^-$. This lepton number violating process would arise from majorana neutrino exchange. In fact, as shown in ref. [12], a nonvanishing $\beta\beta_0$ decay rate requires neutrinos to be majorana particles, irrespective of which mechanism induces it. This establishes a very deep connection which, in some special models, may be translated into a lower limit on the neutrino masses. The negative hints for neutrino masses that follow from the above limits there are some positive hints for neutrino masses that follow from the following cosmological, astrophysical and laboratory observations.

2. Hints for Neutrino Mass

In addition to the above limits there are some positive hints for neutrino masses that follow from the following cosmological, astrophysical and laboratory observations.

2.1. Dark Matter

Recent observations of cosmic background temperature anisotropies on large scales by the COBE satellite [13], when combined with cluster-cluster correlation data e.g. from IRAS [19], indicate the need for the existence of a hot dark matter component, contributeing about 30% to the total mass density [20]. A good fit is provided by a massive neutrino, such as as a $\nu_e$ of a few eV mass. This suggests the possibility of having observable $\nu_e$ to $\nu_\tau$ or $\nu_\mu$ to $\nu_\tau$ oscillations that may be accessible to the CHORUS and NOMAD experiments at CERN, as well as at the proposed P803 experiment at Fermilab [21]. This mass scale is also consistent with the recent hints reported here by Caldwell [22].

2.2. Solar Neutrinos

The data collected up to now by the two high-energy experiments Homestake and Kamiokande, as well as by the low-energy data on pp neutrinos from the GALLEX and SAGE experiments still pose a persisting puzzle [23, 24].

Comparing the data of GALLEX with the Kamiokande data indicates the need for a reduction of the $^7$Be flux relative to the standard solar model expectation. Inclusion of the Homestake data only aggravates the discrepancy, suggesting that the solar neutrino problem is indeed a real problem.

The simplest astrophysical solutions to the solar neutrino data are highly disfavored [25]. The most attractive way to account for the data is to assume the existence of neutrino conversions involving very small neutrino masses $\sim 10^{-3}$ eV [26]. The region of parameters allowed by present experiments is given in ref. [27]. Note that the fits favour the non-adiabatic over the large mixing solution, due mostly to the larger reduction of the $^7$Be flux found in the former.

2.3. Atmospheric Neutrinos

An apparent decrease in the expected flux of atmospheric $\nu_\mu$’s relative to $\nu_e$’s arising from the decays of $\pi$’s, $K$’s and secondary muon decays produced in the atmosphere, has been observed in two underground experiments, Kamiokande and IMB, and possibly also at Soudan2 [28]. This atmospheric neutrino deficit can be ascribed to neutrino oscillations. Although the predicted absolute fluxes of neutrinos produced by cosmic-ray interactions in the atmosphere are uncertain at the 20 % level, their ratios are expected to be...
accurate to within 5%.

Combining these experimental results with observations of upward going muons made by Kamiokande, IMB and Baksan, and with the negative Frejus and NUSEX results leads to the following range of neutrino oscillation parameters:

\[ \Delta m^2_{\mu\tau} \approx 0.005 - 0.5 \text{ eV}^2, \sin^2 2\theta_{\mu\tau} \approx 0.5 \] (4)

Recent results from Kamiokande on higher energy neutrinos strengthen the case for an atmospheric neutrino problem.

3. Models Reconciling Present Hints.

Can we reconcile the present hints from astrophysics and cosmology in the framework of a consistent elementary particle physics theory? The above observations suggest an interesting theoretical puzzle whose possible resolutions I now discuss.

3.1. Three Almost Degenerate Neutrinos

It is difficult to reconcile these three observations simultaneously in the framework of the simplest seesaw model with just the three known neutrinos. The only possibility is if all three neutrinos are closely degenerate.

It is known that the general seesaw models have two independent terms giving rise to the light neutrino masses. The first is an effective triplet vacuum expectation value which is expected to be small in left-right symmetric models. Based on this fact one can in fact construct extended seesaw models where the main contribution to the light neutrino masses (\( \sim 2 \text{ eV} \)) is universal, due to a suitable horizontal symmetry, while the splittings between \( \nu_e \) and \( \nu_\mu \) explain the solar neutrino deficit and that between \( \nu_\mu \) and \( \nu_\tau \) explain the atmospheric neutrino anomaly.

3.2. Three Active plus One Sterile Neutrino

The alternative way to fit all the data is to add a fourth neutrino species which, from the LEP data on the invisible Z width, we know must be of the sterile type, call it \( \nu_S \). The first scheme of this type gives mass to only one of the three neutrinos at the tree level, keeping the other two massless. In a seesaw scheme with broken lepton number, radiative corrections involving gauge boson exchanges will give small masses to the other two neutrinos \( \nu_e \) and \( \nu_\mu \). However, since the singlet neutrino is superheavy in this case, there is no room to account for the three hints discussed above.

Two basic schemes have been suggested to reconcile all three hints. In addition to a light sterile neutrino \( \nu_S \), they invoke additional Higgs bosons beyond that of the standard model. In these models the \( \nu_S \) either lies at the dark matter scale or, alternatively, at the solar neutrino scale. In the first case the atmospheric neutrino puzzle is explained by \( \nu_\mu \) to \( \nu_S \) oscillations, while in the second it is explained by \( \nu_\mu \) to \( \nu_\tau \) oscillations. Correspondingly, the deficit of solar neutrinos is explained in the first case by \( \nu_e \) to \( \nu_\tau \) oscillations, while in the second it is explained by \( \nu_e \) to \( \nu_S \) oscillations. In both cases it is possible to fit all observations together. However, in the first case there is a clash with the bounds from big-bang nucleosynthesis. In the latter case the \( \nu_S \) is at the MSW scale so that nucleosynthesis limits are satisfied. They single out the nonadiabatic solution uniquely. Note however that, since the mixing angle characterizing the \( \nu_\mu \) to \( \nu_\tau \) oscillations is nearly maximal, the second solution is in apparent conflict with eq. 4 but agrees with Fig. 5 of ref. [3]. Another theoretical possibility is that all active neutrinos are very light, while the sterile neutrino \( \nu_S \) is the single neutrino responsible for the dark matter.

4. Outlook

Besides being suggested by theory, neutrino masses seem to be required to fit present astrophysical and cosmological observations, in addition to the recent LSND hints discussed here.

Neutrinos could be responsible for a wide variety of measurable implications at the laboratory. These new phenomena would cover an impressive range of energies, starting with \( \beta \) and nuclear \( \beta\beta_{0\nu} \) decays. Searches for the latter with enriched germanium could test the quasidegenerate neutrino scenario for the joint explanation of hot dark matter and solar and atmospheric neutrino anomalies. Moving to neutrino oscillations, here one expects much larger regions of oscillation parameters in the \( \nu_e \) to \( \nu_\tau \) and \( \nu_\mu \) to \( \nu_\tau \) channels will be be probed by the accelerator experiments at CERN than now possible with present accelerators and reactors. On the other hand more data from low energy pp neutrinos as well as from Superkamiokande, Borexino, and Sudbury will shed light on the solar neutrino issue.

For the far future we look forward to the possibility of probing those regions of \( \nu_\mu \) to \( \nu_e \) or
νS oscillation parameters suggested by present atmospheric neutrino data. This will be possible at the next generation of long baseline experiments. Similarly, a new generation of experiments capable of more accurately measuring the cosmological temperature anisotropies at smaller angular scales than COBE, would test different models of structure formation, and presumably shed further light on the need for hot neutrino dark matter.

Neutrinos may also imply rare processes with lepton flavour violation, as well as new signatures at LEP energies and even higher. Such experiments may be complementary to those at low energies and can also indirectly test neutrino properties in an important way.

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