Neutrino Properties

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This is convenor's summary talk of the "Neutrino Models and Properties" section of the Workshop.

Neutrino properties were discussed not only at the sessions of the "Neutrino Models and Properties" section of the Workshop, but to one or another extent also in many other talks. Therefore, in addition to reviewing the "models and properties" sessions, I shall also briefly touch upon some of these talks. Neutrino mass models are summarized in the talk of F. Feruglio [1].

1. Neutrino properties

Although we now know a lot about neutrinos – that there are three active neutrino species, that they most likely oscillate and so are massive, that at least one leptonic mixing angle is large while at least one other mixing angle is small or zero, and that there is a hierarchy of the mass squared differences $\Delta m^2_\odot \ll \Delta m^2_{atm}$, there are still many questions to which we do not have answers yet. Here some of these questions are listed:

• How many light neutrino species are there? In other words, are there any light sterile neutrinos? If yes, how many?

• What is the nature of neutrinos? Are they Dirac or Majorana particles?

• What is the spectrum of neutrino masses? In the 3-ν case, are neutrino masses hierarchical or quasi-degenerate? In the former case, do they have the direct or inverted hierarchy? If there are four light neutrino species, does the neutrino mass spacing follow the 2+2 or 3+1 scheme? What is the value of $\Delta m^2_\odot$?

• What are the lepton mixing angles? In the 3-ν case, is the mixing angle θ_{23} responsible for the atmospheric neutrino oscillations exactly 45°, the current best-fit value? If not, how close is it to 45°? What is the value of the mixing angle θ_{12} that governs the solar neutrino oscillations? How small is the mixing angle θ_{13} which determines the value of the leptonic mixing parameter U_{e3}? Can we understand why θ_{23} is large (unlike the quark mixing angles) whereas θ_{13} is small? In the 4-ν case, what are the values of the six lepton mixing angles θ_{ij}?

• Is there leptonic CP violation? If yes, how strong is it? Are there Majorana CP-violating phases in addition to the usual Dirac one(s)?

• What are the electromagnetic properties of neutrinos? How large are their magnetic dipole moments? Do they have electric dipole moments?

• Do neutrinos have exotic properties, like flavor changing neutral current interactions or gravitational interactions violating the equivalence principle? Are neutrinos stable? If not, what are their lifetimes and decay modes?

Some of these questions were addressed in the talks given at the Workshop.

1.1. How many neutrino species are there?

Electron and muon neutrinos have been known to exist since 1955 and 1964, respectively. Although there were strong theoretical and indirect experimental reasons to believe that there exist the third neutrino species, ν_τ, until recently it was not unambiguously experimentally detected. In July of 2000 the DONUT Collaboration has reported the direct experimental evidence for ν_τ, which was described at this Workshop by K. Okada [2].

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LEP experiments at CERN have told us that there are only 3 light active neutrino species. There is an astrophysical bound on the number of light neutrinos $N_\nu \leq 3.4$, which applies also to sterile neutrinos provided that they are in equilibrium with matter at the nucleosynthesis epoch. However, this limit is less reliable than the laboratory one, and probably four neutrino species can still be tolerated [3]. As was stressed in the talk of C. Giunti, solar and atmospheric neutrino data and the LSND result, if all interpreted in terms of neutrino oscillations, imply the existence of at least one light sterile neutrino species. The LSND result has not been independently confirmed yet, and we have to wait for the results of the MiniBooNE experiment which will unambiguously test it.

1.2. Dirac or Majorana?

The only practical way of answering this question, known at the moment, is to look for the neutrinoless double beta decay, which can only occur if neutrinos are Majorana particles. $2\beta 0\nu$ decay was searched for experimentally but up to now have not been discovered (see the talk of H. Klapdor [4]). The experiments allowed to put upper bounds on the effective Majorana neutrino mass, the best limit coming from the Heidelberg – Moscow experiment on 2β decay of ^{76}Ge [4]:

$$\langle m_{\nu_e} \rangle_{\text{eff}} < 0.35 \text{ eV} \quad \text{at } 90\% \text{ c.l.}. \tag{1}$$

If $2\beta 0\nu$ decay is discovered, it will be possible to infer the value of the effective Majorana neutrino mass $\langle m_{\nu_e} \rangle_{\text{eff}}$. This would give the lower limit on the mass of the heaviest neutrino.

1.3. Neutrino mass spectrum

In the 3-ν case, neutrino mass spectrum can be either hierarchical (direct or inverted hierarchy) or quasi-degenerate. There are several arguments in favor of the hierarchical neutrino mass spectrum: (i) all other known fermions have hierarchical masses; (ii) the seesaw mechanism seems to predict hierarchical neutrino masses $m_i \sim m_{Di}^2/M_R$, where m_{Di} are (presumably hierarchical) Dirac-type neutrino masses and M_R is the right-handed neutrino mass scale; (iii) quasi-degenerate neutrino masses are, in general, unstable against radiative corrections (the same argument applies to some extent to the inverted mass hierarchy which requires two larger-mass neutrino states to be quasi-degenerate). The last argument is, in my opinion, the strongest one. Yet, none of the above arguments is water-tight. Especially the argument (ii) is based on an oversimplified picture of the seesaw mechanism.

There are two arguments in favor of quasi-degeneracy of neutrino masses: (a) quasi-degenerate neutrinos with $m_\nu \sim$ a few eV can constitute hot dark matter of the universe. This scenario, however, is no longer favored as it seems now that the large-scale structure of the universe can well be explained without hot dark matter. (b) Most importantly, quasi-degenerate neutrinos are perfectly phenomenologically consistent, at least if their mass is below eV.

Neutrino masses can be directly probed in the kinematic and $2\beta 0\nu$ decay experiments; the oscillation experiments probe only the values of Δm^2. Information on β-decay parameters that can be inferred from the neutrino oscillations experiments was discussed by F. Vissani [5].

Neutrino oscillations in 3-ν schemes were discussed in the talks of A. Donini, B. Gavela, T. Kajita, M. Lindner, E. Lisi and H. Minakata [6–11]. The existing data (with the LSND result left out) can be fitted very well in this schemes.

The 4-ν schemes which incorporate the LSND result along with the atmospheric and solar neutrino observations were discussed in the talks of C. Giunti, E. Lisi, A. Marrone and O. Peres [10,12–14]. It was pointed out by E. Lisi and A. Marrone [10,13] that, although oscillations into a pure sterile neutrino state ν_s are disfavored by the data, a significant (up to 60 – 70%) admixture of ν_s in solar and atmospheric neutrino oscillations is possible.

The 2+2 schemes fit all the data well. The 3+1 schemes, which until recently have been considered experimentally disfavored, are now also acceptable as the new analysis of the LSND data yields a smaller than before oscillation probability $P_{\mu e}$. The most attractive 3+1 scheme is the one in which the lone mass eigenstate is predominantly the sterile neutrino; in this scheme the 3-flavour dynamics of solar and atmospheric neutrino oscillations is only slightly perturbed [14].

Possible admixture of ν_s in solar neutrino oscillations can further be tested in the SNO experiment through the CC/NC event ratio and through the comparison of SNO and Super-Kamiokande results. Most direct answer to the question of whether or not light ν_s is necessary will be given by MiniBooNE.

1.4. Leptonic mixing and CP violation

I again start with the 3-ν schemes. Although we know that the mixing angle θ_{23} is equal or close to 45°, the value of θ_{12} is largely unknown. It can be either large (for the LMA, LOW and VO solutions of the solar neutrino problem) or small (for the SMA solution). Solar neutrino experiments are expected to single out the true solution and measure θ_{12} and $\Delta m^2_\odot \equiv \Delta m^2_{21}$ [10,15–17]. The LMA solution can actually be tested by the KamLAND reactor neutrino experiment even before enough solar neutrino data are accumulated to discriminate between different solutions [18].

The mixing angle θ_{13} which determines the value of the leptonic mixing parameter U_{e3} is the least known one: only upper limits on θ_{13} are known, the most stringent one coming from the CHOOZ reactor neutrino experiment [18]. This mixing angle can be probed in future long baseline experiments which are going to study $\nu_e \leftrightarrow \nu_{\mu,\tau}$ appearance, earth matter effects on neutrino oscillations (and so the sign of Δm^2_{32}) and CP violation in the leptonic sector [6,7,9,11]. It can also be probed in reactor neutrino experiments and through the detection of neutrinos from a future galactic supernova.

In the 4-ν case, there are six lepton mixing angles θ_{ij}, and in general the analysis is very complicated. However, it simplifies in phenomenologically interesting cases of 2+2 and 3+1 schemes [10,12–14].

Dirac-type leptonic CP violation can be probed through neutrino oscillations. In the 3-ν case it can in principle be tested at neutrino factories [6,7,9], or in short-baseline low energy experiments [11] provided that the solution of the solar neutrino problem is LMA. Experiments at neutrino factories should also be able to determine the values of Δm^2_{32} and θ_{23} to an accuracy of about 1%. In the 4-ν case, the prospects of testing leptonic CP violation are much better, independently from the solution of the solar neutrino problem [6].

Majorana neutrinos may have additional CP-violating phases, which are not measurable in neutrino oscillation experiments. Majorana-type phases can contribute (CP-even terms) to nuclear 2β decay and radiative neutrino decay rates. However, these rates are extremely difficult to measure (in fact, the latter are practically unmeasurable). In addition, it is very difficult to separate the neutrino Majorana phase contributions to the rates from the conventional contributions.

1.5. Neutrino electromagnetic properties

If neutrinos are massive, they must have magnetic dipole moments μ_ν. In the minimally extended (to include right-handed neutrinos) standard model these magnetic moments are very small [19]:

$$\mu_\nu \simeq 3 \times 10^{-19} \left(\frac{m_\nu}{1\,\mathrm{eV}}\right) \mu_B \,, \tag{2}$$

where μ_B is Bohr's magneton, but in certain extensions of the standard model they can be as large as $(10^{-12} - 10^{-11})\mu_B$. Most stringent laboratory limits on neutrino magnetic moments come from reactor neutrino experiments, the current best limit being [20]

$$\mu_\nu < 1.9 \times 10^{-10} \mu_B \,. \tag{3}$$

The MUNU experiment, discussed in the talk of C. Broggini [21], should be able to improve this limit by a factor of six.

Since with massive neutrinos the lepton flavor is not in general conserved, neutrinos can also have flavor-off-diagonal (transition) magnetic moments. CPT invariance prevents Majorana neutrinos from having ordinary magnetic moments, but they can have transition moments.

Neutrinos may also have diagonal and transition electric dipole moments. Non-zero diagonal electric dipole moments would signify CP non-invariance in the leptonic sector, whereas the transition ones are allowed even if CP is conserved (only simultaneous existence of transition electric and magnetic dipole moments would mean CP violation).

Transition magnetic or electric dipole moments should lead to the radiative decay of heavier neutrinos into lighter ones: $\nu_2 \to \nu_1 + \gamma$, but such processes are essentially undetectable as the expected neutrino lifetimes are comparable with the age of the universe. Transition moments should also lead to a simultaneous spin and flavor flip of neutrinos in magnetic fields (spin-flavor precession). Such a precession can be resonantly enhanced in matter, analogously to the resonance enhancement of neutrino oscillations. Resonance spin-flavor precession of neutrinos provides an alternative solution to the solar neutrino problem, which was discussed in the talks of M. Lusignoli and J. Pulido [22,23].

1.6. Exotic neutrino properties

Unconventional neutrino properties were reviewed by M. Lusignoli and also discussed in a number of other talks at the Workshop. Flavor changing neutral currents, violations of the gravitational equivalence principle and of Lorentz or CPT invariance can all lead to exotic neutrino oscillations which in principle might account for the solar neutrino problem and atmospheric neutrino anomaly, as discussed in the talks of T. Kajita, M. Lusignoli, M. Guzzo, T.K. Kuo and H. Nunokawa [8,22,24–26]. In addition, neutrino decoherence and neutrino decay are also possible explanations of the atmospheric neutrino anomaly [22].

While the solar neutrino problem in general admits solutions based on the exotic neutrino oscillations [24–26], these oscillations generally produce very poor fits of the atmospheric neutrino data, which clearly prefer the conventional neutrino oscillations to the exotic ones. In contrast to this, neutrino decoherence and decay scenarios fit the atmospheric neutrino data very well [22]. The reason for this is that the oscillations and decay (or decoherence) lead to very similar averaged survival probabilities for ν_μ. One could discriminate between the two types of solutions in the experiments like the recently proposed MONOLITH, discussed in the talk of P. Antonioli [27]. The MONOLITH detector will have a much better L/E resolution than that of Super-Kamiokande, and therefore will be able to clearly detect the full first oscillation swing of the ν_μ survival probability (i.e. not only disappearance but also reappearance of ν_μ) in the case of the neutrino oscillation solution of the atmospheric neutrino anomaly.

In the talk of P. Rotelli [28] it was pointed out that some of the derivations of the standard neutrino oscillation formula existing in the literature are incorrect, and the formula itself needs a modification or at least a re-interpretation. In my opinion, the standard oscillation formula is correct and does not need a re-interpretation, although some of its derivations may be oversimplified.

To conclude, we still have to learn much about neutrino properties, but the prospects for this are quite good.

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