Current status of neutrino physics

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Abstract A summary of the current status of neutrino oscillations is given. We also include a brief description of the earlier development of neutrino physics and illustrate the roles that neutrinos play in several areas other than particle physics.

Key words neutrino oscillation, Daya-bay experiment

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1 Introduction-A brief neutrino timeline

The neutrino oscillation and, therefore, massive neutrinos are now well-established facts. They are very important discoveries and very significant advancements made in fundamental science near the end of the last century. The oscillation phenomenon has been observed in many different types of experiments with various neutrino sources. Some of the parameters of the neutrino system, which govern the oscillation, have been determined with about 20% accuracy in the 2σ range. To determine the properties of the system completely, more accurate and challenging experiments, some in progress, some being planned, and more still under study, are necessary to be carried out. With every stage of the experimental progress, theoretical efforts are guided towards a more suitable framework for the neutrino system.

The neutrino saga began in 1930 with the informal proposal of a ghostly particle by Wolfgang Ernst Pauli [1]. Subsequently, Pauli made a formal proposal of the neutrino in 1933 in his talk given at the 7th Solvay Conference [2]. In 1934 Fermi, using the neutrino, proposed the four-fermion theory of beta-decay [3]. The work of Fermi began the quantum field theory formulation of fundamental particle interactions and is, what we know today, an effective theory of the weak interaction. Another important development took place in 1937 with Ettore Majorana's formulation of the Majorana fermion [4] as a real solution of the Dirac equation. It is a development independent of the neutrino. But it turned out that the neutrino is the only candidate for the Majorana particle. And being a Majorana particle, the neutrino would naturally fit into a theoretical scheme which enables it to have a tiny mass among other much more massive particles, when there exists a very large mass scale beyond that of the standard model. Therefore, the implication of Majorana neutrinos is very striking: The physical neutrinos will be fundamentally different from the standard model's neutrinos and other fermions which are Dirac particles, and the tiny neutrino masses necessitate the existence of a very large mass scale which would provide an material evidence for grand unification.

The neutrino was finally observed in 1956 by Reines and collaborators [5] in an experiment with a nuclear reactor which produces electron antineutrinos. Two years later the helicity of the neutrino was measured by Goldhaber [6]. With his confirmation of the existence of the neutrino, Reines recognized that a new cosmic messenger was born. A half century later the neutrino astronomy with the use of the so-called neutrino telescope has become an active experimental research area of fundamental science to explore deeply into the cosmos in time, space, and then structure.

Theoretical ideas that neutrinos can do interesting things began quite early. In 1946 Sakata and Inoue [7] proposed a prototype theory of two types of neutrinos [8]. In 1958 Pontecorvo proposed the neutrino-antineutrino mixing [9]. Neutrino flavor mixing and

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oscillation was proposed by Maki, Nakagawa and Sakata [10] in 1962, and by Pontecorvo [11] in 1968 after the observation of a second species of neutrinos [12], i.e. the muon neutrino, in 1962. A more complete description of this early history of the neutrino oscillation can be found in Refs. [13] and [14] [1)].

The first attempt of observing cosmic neutrino was made by Davis and collaborators [16] in as early as 1968. It is the beginning of the neutrino oscillation industry which has continued for 40 years and more is being pushed into the next few decades. Mixing of states which cause the transition of one state to another is a common quantum mechanical phenomenon. It requires that the masses of the states that mix are not degenerate. For neutrinos, this simple fact provides a powerful information for a very important piece of physics, i.e., some or all species of neutrinos have non-vanishing mass, a definite manifestation of physics beyond the standard model.

As noted above the experimental establishment of neutrino oscillation has been made in a number of experiments with various neutrino sources during the final decade of the last century. A wealth of information on many aspects of neutrinos and neutrino oscillations can be found in the Neutrino Oscillation Industry website [17]. A felicitous testimony of the importance of the study of the neutrino is the fact that there have been to date three Nobel prizes to its credit, once every seven years since 1988: 1988, 1995, 2002.

We can summarize the the recent stages of development of neutrino oscillation physics as follows:

- The first convincing neutrino oscillation signal is provided by the atmospherical neutrino experiment at Super-K [18], following several earlier indications of the oscillation. Now neutrino oscillation has been clearly demonstrated in many experiments at many different laboratories, with both cosmic and terrestrial neutrino sources from the sun, atmosphere, reactors, and accelerators. Several detector types have been used. Concise reviews can be found in many recent conference talks, for an example [19].

- The experimental data available to date, which are limited to the accuracy of the dominant mixing effect, can be understood in terms of theoretical frameworks of two-level vacuum oscillations and adiabatic conversion in matter [20].

- The large mixing angles (at least 2 of the 3) and small masses of the neutrino system are in stark contrast to the mixing and mass patterns of the quarks, posting an interesting challenge to a unified theoretical understanding.

- The supernova events of SN1987A [21] confirmed the existence of intergalactic neutrinos and opened up a new area of astrophysics study, giving birth the so-called neutrino astronomy. The advancement of our knowledge of neutrinos has greatly expanded our tools of study for astrophysics. Neutrino detectors, located deep underground and in ocean, are used as neutrino telescopes to probe regions of stars and the cosmos that are not accessible to the electromagnetical radiation. Several experiments of such kinds are in progress. A list of neutrino telescopes can be found in Ref. [17] and reviews of some recent status are summarized in Ref. [22].

- The experimental advancement in neutrinos has critically influenced the counterpart of theoretical efforts, such as the theory of neutrino mass, possible special role that neutrinos may play in cosmology, etc. Overall, even after the active development of more then a decade, this is still an experimentally driven area in which some important questions have to be answered through more precision experimentation before we can know how to construct a suitable theoretical framework for the neutrino system.

2 Status of the parameters of the neutrino system

Taken to be Majorana particles, the 3-flavor neutrino system consists of 9 parameters. They are 3 masses: m_1, m_2, and m_3; 3 mixing angles: θ_{12}, θ_{13}, θ_{23}, and θ_{13}; and 3 CP-violation phases: $\delta_{\rm CP}$, ϕ_1, and ϕ_2. Due to the unitarity condition and the quantities that the oscillation experiments are sensitive to, not all oscillation experiments are independent. So there are not enough independent oscillation experiments to determine all the 9 parameters. Oscillation experiments all taken together can determine 6 independent parameters: (1) all three mixing angles: θ_{12}, θ_{13}, θ_{23}, and θ_{13}; (2) two mass-square differences: $\Delta m^2_{21}=m^2_2-m^2_1$ and $\Delta m^2_{31}=m^2_3-m^2_1$; and (3) one CP

1) For other earlier pivotal theoretical developments, including Fermi's four-fermion theory of β-decay which ia also related to the 1933 Solvay Conference, see Ref. [15] for a detailed exposition.

phase: $\delta_{\rm CP}$. The phase angle $\delta_{\rm CP}$ is usually referred to as the Dirac phase. The remaining two phases, ϕ_1, and ϕ_2, are called Majorana phases and are absent form oscillation experiments.

To determined all the parameters, experiments outside oscillations are needed. They include the cosmological observation of the neutrino contribution to the total energy content of the universe; beta decays which measure a definite combination of neutrino masses and mixing angles; and neutrinoless double beta-decays, in which the Majorana phases together with the mixing angles and masses enter in the decay matrix element. We will come back to these topics later.

2.1 Parameters determined from oscillation experiments

Although the neutrino oscillation has been established beyond any doubt, the accuracy of the existing experiments are still not high enough. Because of the two well-separated mass-square scales which control the oscillation patterns, in the leading order of the theoretical analysis, each type of experiments has two parameters to deal with, which are the relevant mixing angle and mass-square difference. It has been found that the different types of experiments, that measure the same set of parameters with cosmic or terrestrial neutrino sources, are complementary. Table 1 lists the major experiments, their neutrino sources, and the parameters they measure.

Table 1. Major neutrino oscillation experiments, neutrino sources, and parameters measured.

ν source	parameters	experiments
atmosphere $\nu_\mu, \bar{\nu}_\mu$	$\theta_{23}, \lvert\Delta m^2_{31}\rvert$	Super-K, MACRO, Sudan
cosmic		
solar $\nu_{\rm e}$	$\theta_{12}, \Delta m^2_{21}$	Super-K, SNO
cosmic		
accelerator $\nu_\mu, \bar{\nu}_\mu$	$\theta_{23}, \Delta m^2_{31}$	K2K, MINOS, LSND,KARMEN,MiniBooNE
terrestrial	atmoshperic	
reactor $\bar{\nu}_{\rm e}$ (long baseline)	$\theta_{12}, \lvert\Delta m^2_{31}\rvert$	KamLAND
terrestrial	solar	
reactor $\bar{\nu}_{\rm e}$ (short baseline)	$\theta_{13}, \lvert\Delta m^2_{31}\rvert$	Chooz, Palo Verde (upper bound)
terrestrial		

Table 2. Experimental results from the global fits of SBGV [23] and BRO [24].

parameter	central value		2σ range	
(Δm^2 in eV^2)	SBGV	BRO	SBGV	BRO
$\Delta m^2_{21}(10^{-5})$	7.6	7.66	$7.3-8.1$	$7.31-8.01$
$\lvert\Delta m^2_{31}\rvert(10^{-3})$	2.4	2.38	$2.1-2.7$	$2.11-2.65$
$\sin^2\theta_{12}$	0.32	0.326	$0.28-0.37$	$0.322-0.331$
$\sin^2\theta_{23}$	0.50	0.45	$0.38-0.63$	$0.36-0.611$
$\sin^2\theta_{13}$	0.007	<0.032	<0.033	-
$\delta_{\rm CP}$	–	–	–	–

Recent data analyses have been performed with global fits in the full three flavors of neutrinos. Global fits are now convergent to agree with one another within the experimental uncertainties. In Table 2 we list the results of two representative groups: the Stony Brook, Garching, and Valencia group (SBGV) [23] and the Bari, Rome, and Oxford group (BRO) [24]. BRO also takes into account the cosmologic bound on the neutrino masses. It should be noted that the Beijing Institute of High Energy Physics (IHEP) cosmology group has also obtained a similar fit of the cosmological bound on neutrino masses in their fits of cosmological parameters [25]. We see that the mixing parameters θ_{12}, θ_{23}, Δm^2_{21}, and the magnitude of Δm^2_{31} are known with about 20% in the 2σ accuracy. The sign of Δm^2_{31} and $\delta_{\rm CP}$ are not known. θ_{13} has an upper limit and is expected to be small.

2.2 Some details of parameter fits

In a typical neutrino experiment the statistics is generally never too abundant due to the small cross sections of neutrino interaction. Hence multitude of complementary experiments which are sensitive to different parts of the parameter space have to be carried out. This is illustrated in the data fit of the SBGV [26]. In the fit of the mass-squared difference vs mixing angle, terrestrial and cosmic experiments have different sensitivities. Terrestrial experiments are more sensitive to mass-square differences and cosmic experiments to mixing angles. The figures in Fig. 1 illustrate this interesting feature.

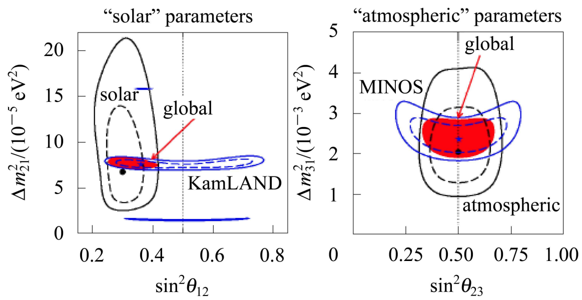

Fig. 1. The interplay of the terrestrial and cosmic data in the determination of the atmospheric and solar neutrino oscillation parameters. The figures are taken from Ref. [26].

2.3 Global fits of θ_{13}

The current information on θ_{13} is mainly derived from the reactor experiment Chooz [27] and from global fits including other relevant data. The upper bound of θ_{13} so obtained depends on the approach of the analysis . We quote two most recent fits obtained by the SBGV and BRO groups which can be found in Refs. [28] and [29]. The results of SBGV [28] are shown in Eq. (1) and Fig. 2, and the results of BRO [29] in Eq. (2) and Fig. 3.

$$\sin^2\theta_{13} = 0.015 \pm 0.010 \tag{1}$$

in 1σ, and

$$\sin^2\theta_{13} \leqslant \begin{cases} 0.060(0.089) & (\text{solar}+\text{KamLAND}) \\ 0.027(0.058) & (\text{Chooz}+\text{Atm}+ \\ & \text{K2K}+\text{MINOS}) \\ 0.035(0.056) & (\text{globaldata}) \end{cases} \tag{2}$$

at 90% CL (3σ). These results hint a non-vanishing θ_{13}.

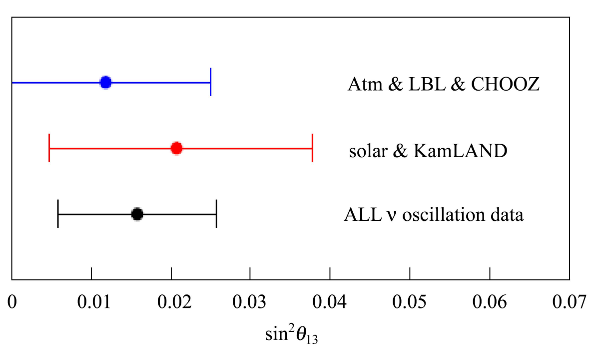

Fig. 2. The range of values of $\sin^2\theta_{13}$ from global fits with different sets of input data. The figure is taken from Ref. [28].

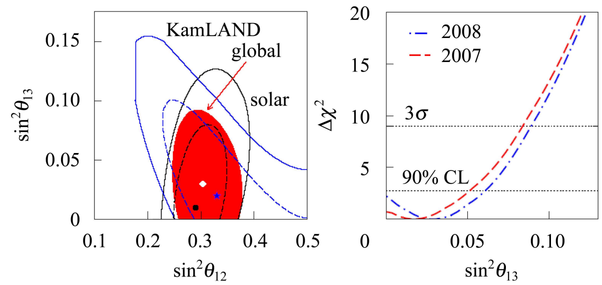

Fig. 3. Range of values of $\sin^2\theta_{13}$ obtained in fits that include different sets of data. The figures are taken from Ref. [29].

2.4 Cosmological bound on neutrino masses

Neutrino oscillation experiments are not sensitive to individual masses of the neutrinos, however, cosmological observation can provide a bound on the sum of the masses of the three neutrinos $\Sigma_{\nu m} = m_1+m_2+m_3$ [30]. The present accuracy of cosmological data, analyzed by several groups, all led to an upper bound of $\Sigma_{\nu m}$. However, an unique upper bound does not yet exit. Different analyses obtain different values of the upper bound, depending on the assumed cosmological models that influence on the number of cosmological parameters, and the combination of data that are incorporated in an analysis. As an example we quote in Table 3 the results of a recent analysis given in the second article of [24]. Note that we have not included in Table 3 the very tight bound obtained with the inclusion of the Lyα data which contains systematics still under scrutiny. A list of the analyses prior to 2005 can be found in Ref. [31]. We see that $\Sigma_{\nu m}$ is probably bounded by 1 eV, but it could also be smaller.

Table 3. 2σ (95% C.L.) bounds for various representative cosmological data. The results are taken from the second article of Ref. [24].

cosmological data set	$\Sigma_{\nu m}$ (at 2σ) eV
CMB	<1.19
CMB+LSS	<0.71
CMB+HST+SN_Ia	<0.75
CMB+HST+SN_Ia+BAO	<0.60

2.5 Some other key results

Below is a quick summary of other important results, some coming from non-oscillation experiments:

- The result of the LSND collaboration [32] on a sterile neutrino has been refuted by the recent MiniBooNE experiment [33]. The latter has a much higher statistics than the former. Although the LSND sterile neutrino is untenable, the MiniBooNE result does not rule out the existence of exotic neutrinos in general. Undoubtedly search of exotic neutrinos will be continued. Exotic, sterile neutrinos with energy dependent mixing angles and masses, and possibly those with other unconventional properties are compatible with the MiniBooNE data and they are intriguing possibility of new physics [34].

- Among the highly interesting non-oscillation experiments is the neutrinoless double-beta decay ($0\nu\beta\beta$), which, when observed, ascertains the existence of the Majorana neutrino. The Heidelberg-Moscow collaboration has claimed a positive signal in the ^{76}Ge deacy [35]. But the claim has been met with general suspicion [36].

3 Theoretical structure of the neutrino system

A general description of the neutrino system is the Majorana fermion, which is a real representation of the spinor and has no lepton number conservation. An n-flavor Majorana system is describable by n^2 parameters, which inlcude n masses, $n(n-1)/2$ mixing angles and an equal number of CP-phases. Among the CP phases, $(n-1)(n-2)/2$ are referred to as Dirac phases and the rest $n-1$ Majorana phases. In contrast, the parameter counting of a system of n Dirac fermions has the same number of masses and mixing angles, but only the $(n-1)(n-2)/2$, Dirac phases. Oscillation experiments can measure $(n-1)$ mass-square differences, all mixing angles, and the $(n-1)(n-2)/2$ Dirac phases. We have already noted in the above the oscillation parameter counting for 3 flavors. The occurrence of very small masses is natural for a Dirac-Majorana system through the seesaw mechanism, with the implication of the existence of a much higher energy scale than that of the remaining part of the whole system in which the neutrinos are embedded.

Mixing of states is caused by the fact that the mass eigenstates are not diagonal in their interactions. In the case of neutrinos, their interactions with the charged leptons define the flavor states. The charged leptons can be taken as diagonal so that the charge lepton mass states and flavor, or weak, states coincide. Then the mass and weak eigenstates of the neutrino are no longer the same.

Let us denote the neutrino weak or flavor states by ν_α, $\alpha = $ e, μ, and τ, and the mass states by ν_j, $j = 1$, 2, and 3. The two sets of states are related by a unitary transformation which is the mixing matrix, denoted as $U = (U_{\alpha j})$ and generally referred to as the Pontecovor-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{3}$$

The PMNS matrix can be parameterized as, up to a diagonal matrix consisting of Majorana phases,

$$U = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar, reactor} \\ \theta_{12}\approx 35^\circ \\ \Delta m^2_{21}\approx 7.6\times10^{-5}\ \text{eV}^2}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}}_{\substack{\text{reactor, accelerator} \\ \theta_{13}<10^\circ \\ \delta_{CP}=?}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\substack{\text{atmosphere, accelerator} \\ \theta_{23}\approx 45^\circ \\ \Delta m^2_{32}\approx 2.4\times10^{-3}\ \text{eV}^2}} \tag{4}$$

where we have also indicated what physical parameters each sub-matrix of U determines and the status of the parameters. Let us remark that the CP-violation effect depends on the sines of all the three angles. Since θ_{12} and θ_{23} are known to be large, the possibility of measuring the CP phase depends on the size of θ_{13}. Hence θ_{13} is dubbed the gateway to the CP-violation effect of the lepton sector.

The current knowledge of the neutrino system including the relative mass spectrum, flavor contents of the mass eigenstates, and the knowns and unknowns are summarized in Fig. 4. The unknown sign of Δm^2_{31} implies that there are two possible spectra, one is called the normal hierarchy with $m_3 > m_2 > m_1$, and the other the inverted hierarchy with $m_2 > m_1 > m_3$. Note that in either hierarchy ν_3 has the least content in ν_e, depending on the value of $\sin\theta_{13}$. ν_3 is the heaviest state in the normal hierarchy and the lightest in the inverted hierarchy. Presently there is no compelling reasons in favoring one hierarchy over the other.

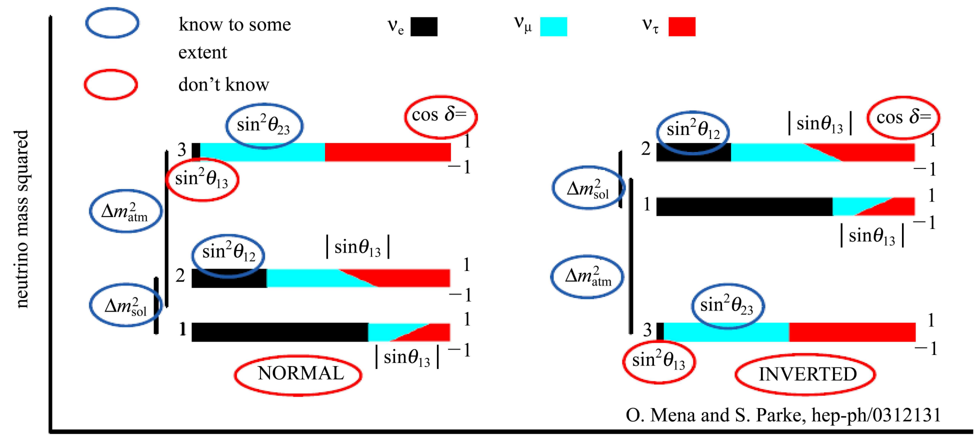

Fig. 4. The neutrino spectra and the flavor content of the mass states. The knows and unknowns are indicated. The figures are taken from Ref. [37].

The information on the individual masses of neutrinos will come from non-oscillation experiments, including nuclear beta decays and cosmological observations. The potential of the cosmological bound of neutrino masses [38] is illustrated in Fig. 5, where $\Sigma_{\nu m}$ is plotted against the mass of the lightest neutrino. The figure also shows the bounds from different sets of cosmological data. For the lightest neutrino mass above 0.1 eV, the two mass hierarchies give the same $\Sigma_{\nu m}$. For the lightest mass below 0.01 eV, however, a determination of $\Sigma_{\nu m}$ may differentiate the two hierarchies.

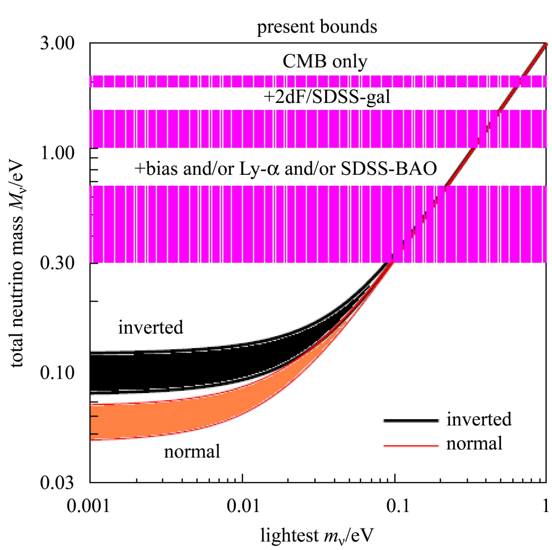

Fig. 5. Bounds on the lightest neutrino mass in the analysis of various cosmological observations which provide limits on the sum of neutrino masses, $\Sigma_{\nu m} = m_1 + m_2 + m_3$. The figure is basically taken from Ref. [38].

3.1 Theoretical constructs of the neutrino mass matrix

Despite the impressive experimental progress and many theoretical models proposed, no compelling theoretical pictures of the neutrino system has yet emerged. Added with the complication of the neutrino system, now the extended standard model takes 22 free parameters to describe. The neutrino system by itself is describable by a mass matrix which should contain the information of the symmetry involved, if any, and the nature of neutrinos as a type of fermions, Majorana or Dirac. Many models of the mass matrix with all sorts of symmetries have been proposed, but there is the lacking of a unifying principle to determine the valid symmetry. This unsatisfactory state of the affairs is perhaps related to the fact that flavor is still one of the least understood aspects of fundamental particles.

Despite the statement above, a simple pattern has appeared out of the information known from the mixing angles. Within 1σ the two large mixing angles can be approximated as $\sin^2\theta_{12} = 1/3$ and $\sin^2\theta_{23} = 1/2$. Furthermore, approximating the small mixing angle $\theta_{13} = 0$, we obtain the so-called tri-bimaximal form of the PMNS matrix [39–41]:

$$U_{\rm TBM} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix}. \quad (5)$$

The regularity of the TBM matrix suggests that it may be dictated by an underlying symmetry of the mass matrix. Many works were inspired to search for the symmetry which may also provide a clue for the flavor symmetry in general[1)]. Various finite non-

1) There is a significant body of literature on the TBM. An extensive list of references can be found in, say, [41].

ablian groups have been propsed for the flavor (horizontal or family) symmetry: A4, A5, S3, S4, Dn, Zm, $\Delta(27)$, $SL_2(F_3)$, tetrahedral group $^{(d)}T$, and broken $SU(3)$ which can all give rise to the TBM. Furthermore, as shown in Ref. [43], the generalized family symmetry of the form $Z_{n1}\times Z_{n2}\dots Z_{nm}$ allows for more than one thousand TBMs and near TBMs. However, it was pointed in Ref. [44] that $S4$ is the only finite group to naturally give rise to the TBM for all Yukawa couplings without fine tuning. It is hoped that, based on the TBM form, a general theoretical construct of a leptonic flavor symmetry can appear. Establishing the lepton flavor symmetry may pave the way towards an understanding of the flavor symmetry for both leptons and quarks, and the fermion mass pattern.

Let us not forget a possible caveat in this inspiring outlook of TBM. That is the value of θ_{13}. In the discussion of the global fit of θ_{13}, we see that the value $\sin^2 2\theta_{13} = 0.1$, which is often quoted as the bound originally given by Chooz, is allowed. Then we have $\theta_{13} \approx 10°$. Even the central value given in Eq. (1), $\sin^2\theta_{13} = 0.015$, gives $\theta_{13} \approx 7°$. Are these values small enough to be approximated by a zero angle?

3.2 Mass varying neutrinos and some of the phenomenology

(MaVaN)-connecting neutrinos with the dark energy

Neutrino oscillation and dark energy are characterized by their respective energy scales: $(2\times 10^{-3}\ \text{eV})^3$ for dark energy and $(0.01\ \text{eV})^2$ for the neutrino oscillation. It is interesting to note that they are both very tiny in their respective normal energy scales and are similar in size. Naturally one would ask if there is a connection between them. The model of mass varying neutrinos (MaVaN) postulates that the dark energy is represented by a dynamic scalar field which couples to neutrinos [45]. This class of models predicts varying effective neutrino masses, depending on the local density of neutrinos. There is also the further dependence on the local matter density that is model dependent. Hence these models can be studied under the environments of large neutrino density and large matter density.

Due to the high neutrino density in the sun, MaVaN should have a significant effect on solar neutrinos and hence the phenomenology of MaVaN can be tested with the existing data of solar neutrinos. It was found in Ref. [46] that a better fit for the solar neutrino data can be obtained when MaVaN is included in the data analysis. As shown in Fig. 6, MaVaN predicts a sharp drop in the solar neutrino survival probability in the region of $E_{\nu_e} = 0.5-0.9$ MeV. MaVaN is marginally favored by the data. More accurate data of solar neutrino below, but near, 1 MeV is needed to provide a definitive test. In Ref. [47] it is found that MaVaN is consistent with both the solar and KamLAND data, and it prefers the normal hierarchy of the neutrino spectrum. Further tests of MaVaN can be made at long baseline neutrino oscillation experiments [48] as shown in Fig. 7.

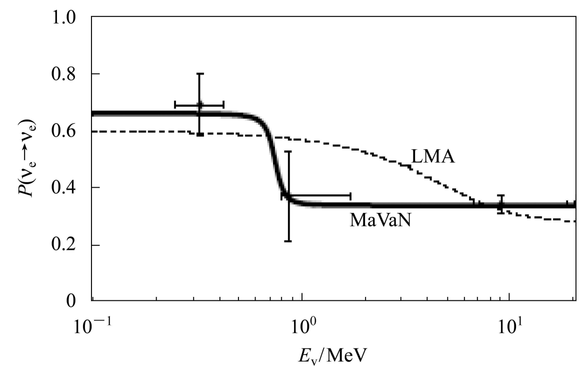

Fig. 6. Solar neutrino data fits with (solid line) and without MaVaN (dashed line). LMA stands for "large mixing angle" which refers to the large mixing angle of the solar neutrino as given in Table 2. The figure is taken form Ref. [46].

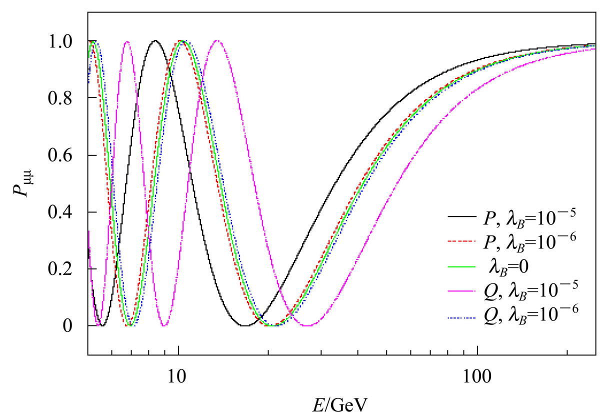

Fig. 7. Prediction of the variation of the ν_μ survival probability $P_{\mu\mu}$ with $(\lambda_B \neq 0)$ and without $(\lambda_B = 0)$ MaVaN as a function of the ν_μ energy in GeV in a very long baseline accelerator experiment. The figure is taken from Ref. [48].

4 Future outlook-some examples

The future study of neutrino physics consists of a broad range of topics and efforts. The experimental programs will be the major efforts and the directions are quite clear. The theoretical efforts, however, require experimental input to provide the necessary clue to pursue in a fruitful direction. Experimental efforts include both oscillation and non-oscillation studies. Very long baseline accelerator experiments are necessary. The goals are:

- Determination of θ_{13}, $\delta_{\rm CP}$, and the sign of Δm^2_{31}.
- Precision measurement of all parameters, matter effect, appearance experiments.
- Determination of the masses of individual neutrinos.
- Determination of what type of particles neutrinos are: Majorana vs Dirac, and Majorana CP phases.

Presently there are new experiments online and under construction, and also proposed ambitious long range plans. The summary given below does not mean to provide a comprehensive picture of the future neutrino programs, but offers some illustrative examples.

The trend of the phenomenological study is to use global-cosmic data to gain understanding of neutrinos. On the basic tenet that neutrinos enter many branches of physics, global fits of all relevant data taken together are to be made. Let us summarize the oscillation and non-oscillation experiments and the parameters they will measure:

- The Dirac phase $\delta_{\rm CP}$ and the sign of Δm^2_{31} can be measured in very long baseline accelerator experiments with the help of the earth matter effect, together with the precision determination of the known oscillation parameters.
- Precision cosmological data for
$$\Sigma_{\nu m}\equiv\sum_j m_{\nu_j}\,. \tag{6}$$
- Beta decays end-point measurement for
$$M_{\beta}\equiv|U_{{\rm e}j}|=\sqrt{C^2_{13}C^2_{12}m^2_1+C^2_{13}S^2_{12}m^2_2+S^2_{13}m^2_3}\,. \tag{7}$$
- Neutrinoless double beta-decays ($0\nu\beta\beta$) lifetime measurement for
$$M_{\beta\beta}=|C^2_{13}C^2_{12}m_1+C^2_{13}S^2_{12}m_2{\rm e}^{{\rm i}\phi_1}+S^2_{13}m_3{\rm e}^{{\rm i}\phi_2}|. \tag{8}$$

4.1 Neutrino programs in Europe and China

They involve most of the experiments in progress or currently under construction:

- A new generation of reactor experiments to measure θ_{13} which include the Daya Bay experiment [49] in China and Double Chooz [50] in France. Both are under construction. Their designed sensitivities are to measure $\sin^2 2\theta_{13}$ down to 0.01 for Daya Bay and 0.03 for Double Chooz. They are expected to be online around 2010. Several issues on the neutrino mass matrix as well as the future direction of neutrino oscillation program depend on the outcome of these experiments.
- Major neutrino programs in Europe are carried out mostly at the Gran Sasso underground laboratory, LNGS [51]. The following projects are in progress.
  - Borexino [52]: Solar ^{7}Be neutrinos from the center of the sun.
  - OPERA [53]: The study of ν_τ appearance in the CERN ν_μ beam.
  - LVD [54]: Search for $\bar{\nu}_{\rm e}$ from gravitational collapse supernova.
  - ($0\nu\beta\beta$): GERDA [55] and CUORICINO/CUORE [56].

4.2 Neutrino program in the US

P5 (Particle Physics Project Prioritization Panel) [57] has recommended neutrino physics as a core component of the US particle physics program, roughly defined as follows:

- Support reactor experiments and neutrinoless double beta decay experiment as the near term priorities in neutrino physics. The reactor experiments are the Daya Bay and Double Chooz collaborations for the measurement of the θ_{13} mixing angle.
- NOνA (NuMI Off-axis ν_{e^-} appearance experiment) [58]: A second generation long baseline experiment considered to be a key program for FNAL, but its future status is now unclear.
- To focus on a multi-megawatt proton source at Fermilab for a high flux neutrino beam, to construct a neutrino beamline to and a large neutrino detector at DUSEL (Deep Underground Science and Engineering Laboratory) at the former Homestake mine.

4.3 Neutrino programs in Japan

Japan has been the major player of neutrino physics for close to two decades. The program of the immediate future is the T2K long baseline accelerator neutrino oscillation experiment [59] as the successor of K2K. It will have a high intensity neutrino beam from J-PARC (Japan Proton Accelerator Research Complex) 295 km away. The main goals of T2K include:

- To observe ν_e from ν_μ (probably for the first time ever).
- To measure $\sin^2 2\theta_{13}$ better by a factor of 10 or 20 than the existing limit.
- To measure Δm^2_{31} and θ_{23} to a few per cent.

4.4 Very long range plans

The very long range plans are difficult to fathom. The following is perhaps a reasonable outline:

- Neutrino superbeams: There have been many investigations of high intensity proton accelerator for very high luminosity neutrino beams in Japan and the USA. This is one possible route of the ultimate study of the parameters and possible exotic properties of neutrinos. Upgrading the number of protons-on-target at J-PARC is a real possibility.
- The neutrino factory (muon collider) has also been discussed extensively in Japan and the US. Many technic details R&D are necessary to make it feasible.
- The beam and detector designs in a very long range plan are necessary parts of the study of future neutrino programs. They will be guided by what we can learn in the near term programs, especially on the value of θ_{13}.

At the time of this writing, the North American and West European financial crisis has happened and reverberated world wide. The crisis has been dubbed as a financial tsunami and its after effects are unclear, but necessary damaging. Undoubtedly, the budgetary reality and perceptions it entails will restrain the scientists' imagination and make the very long range plans murky at best. Physicists are much less bullish than before when they talk about future very long range programs.

4.5 Non-oscillation experiments

- KATRIN tritium beta-decay [60] is an on-going experiment to reach a fantastic accuracy of $M_\beta \sim 0.2$ eV.
- ($0\nu\beta\beta$) [61]: More experiments are in construction or planned, and better theoretical estimate of the decay matrix elements of the decaying nuclei.
- More precision determination of the cosmological bound on $\Sigma_{\nu m}$.

5 Neutrinos in related areas

The photon and neutrino are special in the zoo of elementary particles. Neutrinos are decoupled a few seconds after the Big Bang and the photon after 3.8×10^5 years. They are early relics of the cosmos evolution, forming respectively the cosmic neutrino background (CNB) and the cosmic microwave background (CMB). They hold some of the deepest secrets of the universe. Similar to the photon, neutrinos are involved in many different areas of fundamental physics. Owning to their weakly interacting property, neutrinos can be used to probe regions which are unaccessible to photons, e.g., the interior of a star and other regions opaque to photons. Hence neutrinos are complementary to the photon in cosmic explorations and, therefore, neutrinos are in the forefront of several areas in their intersects with particle physics.

5.1 Physics beyond the standard model

Neutrino oscillation experiments can be used to study non-standard interactions of neutrinos by comparing very short baseline (reactor) measurements with very long baseline data, and in experiments using higher energy neutrino beams [62]. For non-oscillation experiments, the observation or non-observation of ($0\nu\beta\beta$) can provide information on limits of lepton number non-conservation, right-handed interaction in the left-right symmetry model, leptoquarks, composite quarks, SUSY R-parity non-conservation, etc., [63].

5.2 Neutrinos in nuclear physics

This also involves a broad area of study. The physics of neutrino scattering is of much interests in the theory of nuclear structure [64]. In addition there are several other specific interesting topics. Solar neutrinos can test nuclear reactions in the various channels that take place in the sun. Supernova neutrino spectrum tests neutrino-nucleus scatterings. ($0\nu\beta\beta$) can test nuclear matrix element (NME) to differentiate different nuclear models, e.g., shell model vs pn quasiparticle random-phase approximation, etc.

5.3 Neutrino in astrophysics

Galactic and extra-galactic cosmic neutrinos have been confirmed. To date, two cosmic neutrino sources have been identified: the sun and SN1987A. Neutrinos are a critical component of astrophysical phenomena. Large stars in their deathbed can emit intense burst of neutrinos to release their energy. To study these neutrinos is critical to the understanding of the details of how stars evolve. The SNO neutrino oscillation experiment has confirmed the solar model and established the thermal nuclear reactions as the energy source of star burning. The SN1987A has confirmed a basic explosion mechanism of the supernova, but more data are needed for the detailed study.

Because they are neutral and have only weak interactions, neutrinos are sensitive to small non-standard interactions in astrophysics. The research frontiers can be classified by three energy scales which can be studied by neutrino telescopes [65]: (1) the MeV (10^{-6} TeV) scale. This consists of the visible part of the universe, such as the solar neutrino and the SN neutrino. Many of the neutrino oscillation experiments also operate in this energy scale. (2) the TeV scale. This is the nonthermal region of the universe. An example is the jet powered by black holes. Some of the online neutrino telescopes are working in the regime characterized by this energy scale, such as AMANDA and its successor IceCube [66]. (3) The EeV (10^{6} TeV) scale. This is the extreme universe, which forms the very high energy frontier of neutrino physics. The neutrino energy can exceed the GKZ cutoff (4.2×10^{19} eV). Detailed exposition of the various aspects of neutrino astrophysics can be found in Refs. [65] and [67].

5.4 Neutrinos in cosmology

Neutrinos play an important role in the early universe by their intervention in the earlier stage of the evolution of the cosmos [68]: big bang nucleosynthesis, anisotropies of CMB, formation of large scale structure, etc. Neutrinos can be a component of the dark matter. Light warm dark matter, a right-handed sterile neutrino, can be used to resolve a number of problems [69]. Neutrinos can contribute to baryon asymmetry through leptogenesis, and probe the Planck scale physics [70]. Neutrinos may be closely related to the dark energy as in MaVaN models discussed earlier above.

5.5 A wobbly neutrino? 1)

An unusual behavior was found recently in the decay of two radiative isotopes ^{140}Pr (praesodymium) and ^{142}Pm (promethium) [72]. Instead of the usual exponential decay curves, periodic oscillations have been observed as shown in Fig. 8. The decaying elements used are unusual objects which are highly positive ions of these heavy elements, and the electrons produced in the decays are captured by a vacant electron orbit of the ions. In the experiment masses and decay half-life times of the these ions are accurately determined. The authors tentatively attributed the observation to "the coherent superposition of finite mass eigenstates of the electron neutrinos from the weak decay into a two-body final state".

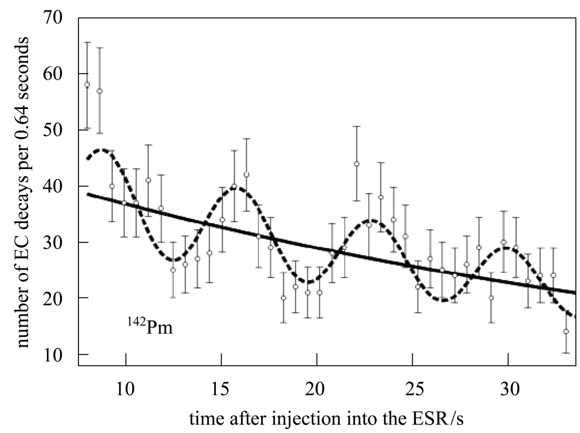

Fig. 8. The oscillation has a period of 7 seconds and ^{140}Pr shows a similar behavior. The figure is taken from Ref. [72].

5.6 Exotic applications of neutrinos

The ubiquitous neutrino possesses a mystic quality that can let loose people's imagination. The following are some examples which have appeared in the arXiv. The authors of Ref. [73] propose that a neutrino beam of 6.3 PeV, which has a resonant scattering with the electron to produce the W-boson $\nu_e+e^-\rightarrow W^-$, be used for intergalactic communications. The information to be transmitted can be coded in the time series of the transmitting neutrino beam. Because of the weakly interacting nature of the neutrino, most cosmic objects along the route of the beam will not post a problem. Another example is the proposal of the construction of a neutrino counter of nuclear weapons [74]. The goal is to use

1) The title is inspired by an article of Nature [71] entitled A neutrino's wobble?".

a neutrino beam to detonate a nuclear warhead in flight. Since there is no shield against neutrino beams this kind of defense against nuclear weapons is expected to be hundred per cent effective.

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