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TOPICAL QUESTIONS IN THE EXPERIMENTAL NEUTRINO PHYSICS* **

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The strong experimental evidence for neutrino oscillations is one of the most exciting recent results in physics. Results obtained in the SuperKamiokande, K2K, SNO and KamLAND experiments are presented. A summary of the future experiments and of the most important measurements concerning the neutrino oscillations is given. The neutrino absolute mass scale, their mass hierarchy and character (Dirac or Majorana particles) are open questions of vital importance. The current and future experiments trying to answer these questions are briefly discussed. A short presentation of the recent experimental searches for ultra high energy neutrinos closes this article.

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1. Introduction

The conference organizers asked me to review the most important experimental facts in the neutrino physics of today and to discuss perspectives for the future. It is a fascinating subject. Recent reviews include, [1–4]. The plenary talks of Lesko [5] and Murayama [6] at the EPS2003 conference in Aachen should also be mentioned. Among the many WEB pages dedicated to neutrino experiments and neutrino physics my favorite one is [7].

Neutrino physics has become a particularly active and attractive field of research since the fundamental discovery of neutrino oscillations by the SuperKamiokande experiment in 1998 [8]. It is enough to say that the

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SuperKamiokande publication [8] has become, in a few years, the most frequently cited paper in experimental particle physics. During this period also three new experiments, K2K, SNO and KamLAND, have started to take data and brought strong additional evidence for the neutrino oscillations.

Several new experiments dedicated to the oscillations are either being prepared or planned. In my opinion, there is a kind of a phase transition between the present and the future experiments. The measurements done by now belong to the romantic era of great discoveries while the future experiments aim at a much more precise determination of the oscillation parameters. In particular, a much better determination of the mixing angle θ_{13} (describing the sub-dominant oscillations in the atmospheric region) is a primary experimental goal in the current decade. Measurement of the CP violation in the leptonic sector is, if at all possible, the ultimate goal. Precision measurements in the case of weakly interacting neutrinos mean an enormous experimental challenge. It is not only a question of huge and preferably high granularity detectors but also of adequate neutrino sources in the form of very intensive accelerator beams or powerful reactors.

The fact that neutrinos oscillate means that they are massive particles, opposite to what had been assumed for decades. In particular, a non-zero neutrino mass is not compatible with the Standard Model describing the elementary constituents of matter and their interactions. Oscillation measurements bring the information about differences of mass squares of the oscillating neutrinos. The neutrino absolute mass scale and the hierarchy of neutrino masses remain open questions of vital importance. Other types of experiments, like direct mass determination based on the tritium beta decay, searches for the neutrinoless double beta decays or cosmological measurements give upper limits of the neutrino masses. The future KATRIN experiment for the tritium beta decay will have sensitivity ten times higher than the present experiments. The main goal of the searches for neutrinoless double beta decays is even more important. It concerns an answer to the fundamental question whether neutrinos are Dirac or Majorana particles. Convincing evidence for the neutrinoless double beta decay would confirm the Majorana character of neutrinos and would be another great discovery in neutrino physics.

A big part of this article is dedicated to the present and future measurements in the domain of neutrino oscillations. It is followed by a summary of the important experimental results in non-oscillation neutrino physics, and a section dedicated to the experiments searching for ultra high energy neutrinos from extraterrestrial point sources.

2. Neutrino sources

Besides the photons, neutrinos are the most abundant particles in the Universe. As shown in Fig. 1 their energies can differ by more than twenty orders of magnitude. On the low edge of the energy scale are the relic cosmological neutrinos, which had been produced at early stage of the Universe while on the upper edge are the very high energy astrophysical neutrinos from the extraterrestrial point-like sources.

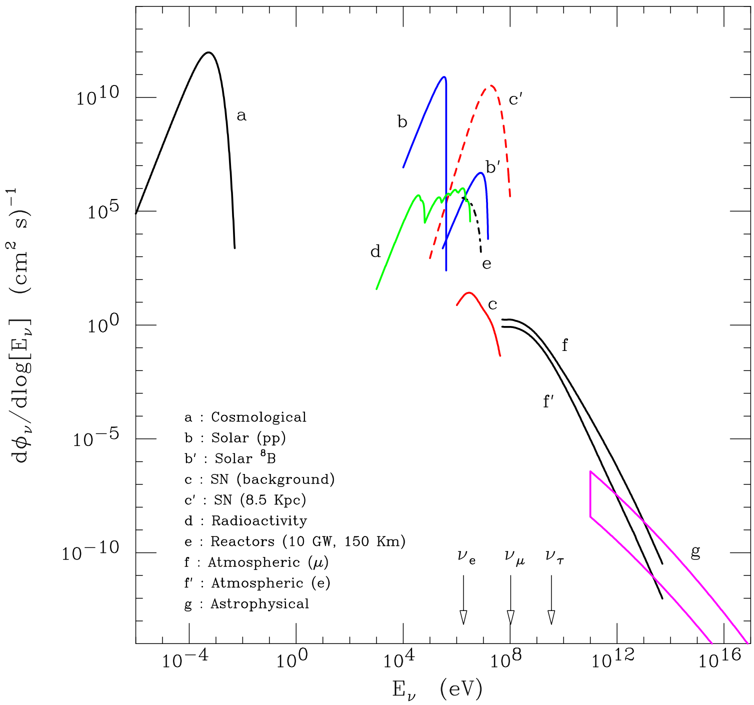

Fig. 1. Fluxes and energy spectra of neutrinos on the Earth (figure from Paolo Lipari — private communication).

The relic, cosmological neutrinos are not detectable with currently available detectors, but the theoretical calculations of their flux are reliable. Studies of the ultra high energy neutrinos have only recently started. Thus, most of the experimental results obtained up to now and presented in this article, concern the interactions of neutrinos of intermediate energies, *i.e.* solar, atmospheric, reactor and accelerator neutrinos. Energies of the accelerator neutrinos, not shown in Fig. 1, cover the lower part of the energy range of the atmospheric neutrinos. Another very interesting source of low energy neutrinos are the Supernova explosions. They are discussed in detail in Kisiel's talk [9].

3. Current status of neutrino oscillations

Neutrino oscillations are by far the best theoretical explanation of the features of all the collected data on the atmospheric, accelerator, solar and reactor neutrinos. Alternative theoretical ideas, *e.g.* the neutrino decay or CPT non-conservation, are not favored by the data (see *e.g.* [1]).

3.1. Theoretical description of oscillations

Before going into discussion of the experimental results let us introduce the formalisms used to describe oscillations. In the simplified case of two oscillating neutrinos, the flavor states ν_α and ν_β are linear combinations of the two mass states ν_1 and ν_2. The probability that the neutrino ν_α of energy E (in GeV) will become a neutrino ν_β after passing a length L (in km) is given by the well-known equation:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27\Delta m^2 \frac{L}{E}\right) \tag{1}$$

while the probability that it will survive as ν_α is

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)\,. \tag{2}$$

The mixing angle θ between the two mass states and the difference of their mass squares Δm^2 (in eV^2) in equation 1 are the theoretical parameters fitted from the data. The experiments looking for a signal from ν_β's in the flux of ν_α's are called appearance experiments, while the experiments looking for a decrease of the flux of ν_α's are named disappearance experiments. Depending on the length L between the neutrino source and the detector, the short baseline (SBL) and the long baseline (LBL) experiments are distinguished.

According to the measurements performed at LEP [10] there are three light, *i.e.* with a mass smaller than half the mass of the Z^0 boson and active, *i.e.* coupling to the Z^0, neutrino flavors ν_e, ν_μ and ν_τ. In the framework of three mixing neutrinos the oscillation probabilities depend in the general case on two differences of the mass squares, three mixing angles between mass states ν_1, ν_2, ν_3 and three phases (one Dirac's and two Majorana's). Within the standard conventions the Maki–Nagakawa–Sakata–Pontecorvo U_{MNSP} mixing matrix can be written as (see *e.g.* [1]):

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$\left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{array}\right) \times \left(\begin{array}{ccc} \cos\theta_{13} & 0 & e^{-i\delta_{\rm CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{array}\right)$$
$$\times \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{array}\right) \times \left(\begin{array}{ccc} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{array}\right). \quad (3)$$

The squared modulus of matrix element $\mid U_{ij} \mid^2$ corresponds to the contribution of the neutrino mass state j to the neutrino flavor state i. The first of the four matrices on the right hand side describes the mixing in the solar neutrino sector and the third one is related to the atmospheric neutrinos. The second matrix mixes the solar and atmospheric neutrinos through the mixing angle θ_{13} and contains the phase related to the CP violation in the neutrino sector. The fourth matrix contains the Majorana phases which enter into the description of the neutrinoless double beta decay, but do not concern oscillations.

If neutrinos travel through a medium of high density, like the interior of the Sun, the matter effects enter into equations (1)–(3) through complicated formulas for the effective oscillation parameters (for details see [1]).

The mathematical formalism becomes much more complicated if more than three mixing neutrinos are considered. In this case the fourth neutrino has to be the so called sterile neutrino, *i.e.* one not coupling to the Z^0 boson. Such formalism and such neutrino(s) would be needed in the case of observing the neutrino oscillations for more than two different values of the Δm^2_{ij}. To what extend the experimental data suggest that, will be discussed further.

3.2. Experimental results

The experiments point to three oscillation regions in the parameter plane of Δm^2 and $\sin^2 2\theta$ (or $\tan^2\theta$). There is solid experimental evidence for two of them, corresponding to the oscillations of the atmospheric and the solar neutrinos. The third region corresponds to the so called LSND effect and requires further experimental studies.

3.2.1. Oscillations of atmospheric neutrinos

Atmospheric neutrinos come from the successive decays of π and K mesons and μ leptons ($\pi^+, K^+ \to \nu_\mu\mu^+ \to \nu_\mu e^+\nu_e\overline{\nu}_\mu$; $\pi^-, K^- \to \overline{\nu}_\mu\mu^- \to \overline{\nu}_\mu e^-\overline{\nu}_e\nu_\mu$), produced in the interactions of cosmic rays with nuclei in the upper part of the Earth atmosphere. Their average energy is around 0.4 GeV. For lower pion energies the ratio of the produced muon to electron neutrinos ν_μ/ν_e is equal two. Then it grows up with energy due to an increase of the number of muons, which reach the Earth before decaying. There is a long story of the measurements of this ratio, which I do not discuss here (for details see [12]).

The statistically significant measurements came from the SuperKamiokande experiment in 1998 [8]. Muons and electrons created in the charged current (CC) ν_μ and ν_e interactions were identified and their energies and directions were measured through the characteristic rings of the Cherenkov radiation, emitted along particle paths in water and registered by photomultipliers covering the detector walls. A detailed description of the 50 kton SuperKamiokande water detector is given in [11].

The SuperKamiokande data analyses include several measurements performed for different categories of events and different energy ranges [8,12,13]. The ratio of the observed number of the μ-like events to the observed number of the e-like events divided by the corresponding ratio simulated under the assumption of no oscillations was found equal $0.688 \pm 0.016 \pm 0.050$. This is significantly different from one, which would be the result if there were no oscillations. Very important are the measurements of the ν_μ and ν_e fluxes as functions of the zenith angle. This dependence is directly related to length of the neutrino path across the Earth (changing from $L \approx 10$–30 km for the neutrinos going down to the detector to $L \approx 13,000$ km for the upward going neutrinos, which traverse the whole diameter of the Earth before entering the SuperKamiokande detector). The measurements showed that the depletion of the ν_μ flux increases with the zenith angle and that the ν_e flux is stable. The measurement of the asymmetry between the fluxes of the upward- and downward-going muons gave the value $-0.303 \pm 0.030 \pm 0.004$ significantly different from zero, which is another proof for the existence of oscillations.

All the data sets are consistent with the same oscillation parameters pointing to the oscillations $\nu_\mu \to \nu_\tau$. Recently the SuperKamiokande reanalyzed the whole data [14] collected up to the detector crash in autumn 2001. They applied an improved calculation of the neutrino flux [15], better ν interaction models and improved detector simulation and reconstruction programs. The preliminary best fit values of the oscillation parameters are $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2 (as compared to $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 from [13]).

3.2.2. K2K accelerator experiment

K2K is the first accelerator long baseline neutrino experiment [16]. The distance from the ν_μ source at K2K to the SuperKamiokande detector is about 250km and the average energy of the ν_μ beam is about 1.3 GeV. Thus E/L corresponds to the oscillation region of the atmospheric neutrinos. The experiment is aimed at looking for the disappearance of the initial ν_μ flux, which is measured by the so-called near detector at KEK with a precision better than 8%.

The comparison is made between the ν_μ flux and energy spectrum measured by the SuperKamiokande far detector and the flux and energy spectrum predicted from the near detector measurements.

The analysis of the whole data collected before the SuperKamiokande accident in autumn 2001 [17] shows both the ν_μ flux depletion (56 observed events as compared to $80.1 \pm 6.2 \pm 5.4$ expected ones) and the modification of the energy spectrum. The K2K data is consistent with the $\nu_\mu \rightarrow \nu_\tau$ oscillation as measured by SuperKamiokande for the atmospheric neutrinos. The best fit values are: $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2, $\sin^2\theta = 1.0$.

3.2.3. Solar neutrinos

The solar ν_e neutrinos are produced in the Sun core in the processes of synthesis of heavier nuclei from the light ones. A detailed discussion of the solar neutrino fluxes and of the energy spectra can be found in [18]. I will only point out that the dominant contribution to the solar neutrino flux (91%)is due to the synthesis of the ^{4}He nucleus out of four protons. Energies of neutrinos from this *pp* cycle are below 0.42 MeV, which makes them very difficult to detect. Energies of the ^{7}Be neutrinos are equal to 386 keV and 863 keV. The real time experiments like the SuperKamiokande and SNO measure only the high energy part (between 5–6 MeV and 20 MeV) of the solar neutrino flux, which is due mostly to the ^{8}B neutrinos. Thus the total solar neutrino flux, discussed in the following, in reality means the flux above the experimental threshold of 5–6 MeV. What concerns the oscillation of solar neutrinos, the formalism which fully takes into account matter effects along the neutrino path from the Sun core to the surface has been developed. Four different solar oscillation regions were allowed barely a few years ago. Three of them (called SMA, LOW and LMA) corresponded to the solar neutrino oscillations inside the Sun. The fourth ("just so") described the oscillations on the way from the Sun surface to the Earth. The fact that solar neutrinos are sensible to the matter effects may cause a difference between the solar flux measured during day and during night. The night flux is expected to be higher, because of the ν_e regeneration inside the Earth on the way from the Sun to the detector.

The story of the so-called solar neutrino puzzle is very long. It has started 35 years ago with the measurements of the solar ν_e flux performed in the Homestake mine [19] which gave roughly one third of the solar neutrino flux expected from the standard solar model (SSM) [20]. R. Davis Jr. got in 2002 the Nobel Prize for this discovery. Details about the studies of neutrinos from the Sun performed by the experiments SAGE, GALLEX, Kamiokande and SuperKamiokande, which have followed the Homestake experiment, as well as the history of the SSM can be found in [18].

The convincing demonstration that the solar neutrino puzzle results from neutrino oscillations has been given only recently by the SNO experiment [21]. The SNO detector is based on the same principle as the SuperKamiokande one *i.e.* it uses the Cherenkov light emitted along the paths of the charged particles. The difference is that the SNO inner detector is filled with heavy water D_2O (about 1000 tons). Due to that the detector can simultaneously measure the ν_e flux in the CC reaction $\nu_e+d \rightarrow p+p+e^-$ and the total neutrino flux $(\nu_e + \nu_\mu + \nu_\tau)$ in the neutral current (NC) reaction $\nu_x + d \rightarrow n + p + \nu_x$, whose cross-section is the same for each type of neutrinos. Only ν_e-s are produced in the Sun. ν_μ and ν_τ, if present, must come from the ν_e oscillations.

The only signal for the NC reaction is the neutron, which can be observed from the capture (n, γ) reaction. Three phases of the SNO experiment had been foreseen. The goal is to increase the neutron detection efficiency ε_N. After a first period of running with pure D_2O ($\varepsilon_N = 24\%$) [21], two tons of salt (NaCl) were added to use the neutron capture on Cl atoms. This increases ε_N to 83%. Now the experiment is at the beginning of its third stage, when special helium counters are deployed in D_2O, which makes possible the event by event separation of the CC and NC reactions.

The SNO detector, like the SuperKamiokande, can also measure the elastic scattering (ES) of neutrinos by atomic electrons. Although this reaction happens for all three flavors, ν_μ and ν_τ contribute only 15% of the total elastic cross-section. Hence its sensitivity to measure the total neutrino flux is much smaller than that of the NC reaction used by SNO. The SNO measurements of the elastic scattering reaction agree within errors with the SuperKamiokande results.

The fluxes measured by SNO are [21]:

$$\begin{aligned}
\Phi_{\rm CC} &= (1.76 \pm 0.05 \pm 0.09) \times 10^6 {\rm cm}^{-2}{\rm sec}^{-1}\,, \\
\Phi_{\rm NC} &= (5.09^{+0.44+0.46}_{-0.43-0.43}) \times 10^6 {\rm cm}^{-2}{\rm sec}^{-1}\,,
\end{aligned}$$

showing the usual suppression of the CC flux and the total flux being in agreement with the total flux given by the SSM: $\Phi_{\rm SSM} = 5.05^{+1.01}_{-0.81}$. The SNO measurements [21] also include studies of the day-night asymmetry.

All SNO results agree with the oscillations of solar ν_e into ν_μ and/or ν_τ. The ambiguity between the two flavors of the generated neutrinos cannot be resolved, because their energies are below the thresholds for their CC interactions.

Recently the SNO experiment has published the results of its second phase [22]. As expected, the measurement errors for the NC reaction significantly decreased. When the SNO measurements are included into the solar oscillation global fit, only the LMA solution survives. The best values of the fitted parameters are [22]: $\Delta m^2_{12} = 6.5 \times 10^{-5}\text{eV}^2$, $\tan^2\theta_{12} = 0.40$ and the flux $f_B = 1.04$. It is worth to notice that the allowed parameter space of the solar oscillations decreased by seven orders of magnitude due to the SNO measurement.

3.2.4. Reactor experiment KamLAND

KamLAND is the LBL reactor experiment "looking" at more than thirty reactors in Japan and Korea at an average distance of about 180 km from the detector. Electron antineutrinos $\overline{\nu}_e$ come from the fission processes. The total $\overline{\nu}_e$ flux is directly related to the produced power; a typical 3 GW power station gives $6 \times 10^{20}\overline{\nu}_e$ per second. The energies E of the reactor $\overline{\nu}_e$-s vary from about 1 MeV to about 8 MeV with the most probable values between 2 and 4 MeV. The resulting values of E/L correspond very well to the solar neutrino oscillation region.

The $\overline{\nu}_e$ are registered through the two-step process $\overline{\nu}_e + p \to e^+ + n$, $n + p \to d + \gamma$. In the KamLAND detector, whose inner part is filled with 1 kton of liquid scintillator, it gives a clear signature due to the prompt signal from the $e^+ + e^-$ annihilation and the delayed (by about $210\,\mu$ sec) signal from the γ of energy 2.2 MeV.

The KamLAND experiment has started data taking in January 2002 and already in December 2002 has published its first results [23], providing the spectacular confirmation of the solar oscillations. They manifest themselves through both the suppression of the initial flux (54 observed events with respect to 86.8 ± 5.6 expected ones) and the modulation of the $\overline{\nu}$ energy spectrum. The best values of the fitted parameters are: $\Delta m^2_{12} = 6.9 \times 10^{-5}$ eV^2, $\sin^2\theta = 0.91$. One should mention that already this low-statistics measurement has significantly reduced the uncertainty in the measurement of Δm^2_{12} from SNO.

3.2.5. LSND effect

Solar and atmospheric oscillations fit very well in the three-neutrino oscillation framework. However, the LSND experiment found evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations [24] in the data for μ^+ decays at rest. The significance of this result is $3.3\,\sigma$. The allowed oscillation region of LSND has been largely suppressed by the KARMEN experiment which found no evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations [25]. The remaining region of the allowed parameter space corresponds to Δm^2_{L} about 0.2–1 eV^2 or 7 eV^2 and a small mixing angle [1].

The independent experiment MiniBOONE which covers the whole parameter space of LSND has started to take data in 2002 [26]. If the LSND oscillations are confirmed, a fourth neutrino (the sterile one) is needed to incorporate the three different values of Δm^2: solar, atmospheric and LSND.

4. Future of neutrino oscillations

The starting point, which is the present knowledge of neutrino oscillations, could be summarized as follows. We already approximately know four out of the six oscillation parameters:

- $|\Delta m^2_{23}|$ and θ_{23} based on the oscillations of the atmospheric and accelerator ν_μ neutrinos (the best fit values are [14]: $|\Delta m^2_{23}| = 2\times10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$ corresponding to the maximal mixing of the mass states ν_2 and ν_3)

- Δm^2_{12} and θ_{12} based on the oscillations of the solar ν_e neutrinos into ν_μ and/or ν_τ neutrinos and of the reactor $\overline{\nu}_e$ into $\overline{\nu}_\mu$ and/or $\overline{\nu}_\tau$. The best fit values are [22]: $\Delta m^2_{12} = 7.1 \times 10^{-5}$ and $\tan^2\theta_{12} = 0.41$, corresponding to the large but not maximal mixing of the mass states ν_1 and ν_2.

The missing information is:

- Value of θ_{13} describing the sub-dominant oscillation $\nu_\mu \to \nu_e$ in the atmospheric region. We only know that this angle is small.

- Sign of Δm^2_{23} — note that the sign of Δm^2_{12} is known due to the matter effects in the Sun, involved in the oscillations of the solar neutrinos.

- Dirac CP phase δ.

The future experimental program can be divided into two phases: measurements done by the running and/or already accepted experiments and the further future experiments now under discussion. The near future measurements will bring further improvements in the determination of the oscillation parameters for the dominant oscillations in the solar and atmospheric regions. The main challenge for the further future experiments is a very precise determination of the θ_{13} mixing angle with the ultimate goal of determining the CP violation in the leptonic sector.

4.1. Solar region

A road map to a better understanding of the solar region is described in [4]. Further measurements of SNO and KamLAND should result in a better determination of Δm^2_{12} and θ_{12}. The allowed 3σ region for Δm^2_{12} should be reduced by a factor of ten after three years of data taking by KamLAND. Then Δm^2_{12} will be known with a precision of about 10%. The reduction of the region allowed for θ_{12} will come mostly from the SNO measurements. It is not expected to be large, but should exclude maximal mixing at a high confidence level.

The BOREXINO experiment [27] dedicated to studies of the ^{7}Be neutrinos will not significantly contribute to the measurement accuracy for θ_{12}. It should, however, considerably reduce the uncertainty in the measured ^{7}Be neutrino flux and in the p–p flux.

A much better determination of θ_{12} could be realized in two ways. Since the Δm^2_{12} will be known from KamLAND with good precision, one could think about the future reactor experiment with a baseline exactly corresponding to a minimum in the survival probability [28] *i.e.* optimal for the θ_{12} determination. For example, the baseline of 70 km corresponds to $\Delta m^2_{12} = 7 \times 10^{-5}$ eV^2.

Another way (strongly advocated in [4]) is a new experiment dedicated to the solar neutrinos from the *pp* cycle. According to the LMA solution, somewhat below 1 MeV there should be a transition from the matter-dominated oscillations to the vacuum oscillations. This change of mechanism could be verified and the vacuum θ_{12} mixing angle could be measured. The p–p neutrinos account for 91% of the total solar flux. The experimental verification of this SSM prediction is very important in order to better understand the production mechanisms of solar energy.

4.2. Atmospheric neutrinos

The SuperKamiokande detector was rebuilt (with about 50 % of the initial photomultipliers) and resumed data taking in December 2002. The atmospheric and accelerator experiments continue as SuperKamiokande-II and K2K-II. The latter should collect a statistics comparable to that of K2K-I, making possible a better determination of the modification of the neutrino energy spectrum due to oscillations.

The other two LBL accelerator programs (NuMI in the USA and CNGS in Europe) are at the preparatory stage. In both cases the baseline is around 730 km. The NuMI program will start in 2005 and the CNGS program in 2006. There will be one experiment (MINOS) running on the NuMI beam and two experiments (ICARUS and OPERA) on the CNGS beam.

The experimental program of MINOS [29] is similar to the K2K program. It is a disappearance experiment, measuring the survival probability $P(\nu_\mu \to \nu_\mu)$. Because the energy of the MINOS beam is adjustable (of course within certain limits), it can be chosen according to the actual best knowledge about the atmospheric oscillations. The main goal of the MINOS experiment is a significant improvement of the Δm^2_{23} and θ_{23} determinations; after three years of data taking by MINOS errors should be reduced to about 10%. There will be two detectors, the near one at the Fermilab and the far one in the Soudan mine, close to the Canadian border. These are similar calorimetric detectors, built of 2.54 cm thick steel plates interleaved with sensitive plates of solid scintillator with a crude granularity. The total weight of the close and far detectors is 0.98 kton and 5.4 ktons respectively.

The CNGS beam will be produced at CERN and sent to the Gran Sasso laboratory in Italy. It will be a high energy beam peaked around 20 GeV. This energy is needed for the production of sufficiently energetic τ leptons because the CNGS program aims at the observation of ν_τ appearance in the initial ν_μ beam. In this way the ν_μ into ν_τ oscillations will be directly proven. There is no near detector (not necessary in this type of experiment), but far detectors (ICARUS and OPERA) are characterized by their fine granularity and capabilities for kinematic measurements, necessary for the background-free searches of the ν_τ interactions. The detailed presentation of the ICARUS experiment has been given in Jan Kisiel's talk, so I will only present a short description of the OPERA experiment [30].

The OPERA detector has been designed to enable identification of the τ leptons produced in the ν_τ CC interactions through their characteristic decay topologies, *e.g.* a kink on the track very close to the ν_τ interaction vertex (for τ leptons $c\tau = 87.11\,\mu m$). The detector is subdivided into two supermodules, each built of a target unit and a magnetic spectrometer. The target units consist of 31 walls of emulsion chambers and scintillator planes. The walls are built with bricks, each of 8.3 kg and containing 56 lead sheets interleaved with emulsion films. Five years of running should result in finding about ten events of ν_τ CC interactions; this number depends quadratically on Δm^2_{23}.

4.3. Measurement of θ_{13}

The determination of θ_{13}, the third mixing angle, which describes the sub-dominant oscillation $\nu_\mu \to \nu_e$ in the atmospheric region, is now the most important measurement in the domain of neutrino oscillations. An upper limit on $\sin^2 2\theta_{13}$ of 0.12 comes from the CHOOZ experiment [31]. A recent publication [32] gives a smaller limit of 0.074 based on the global fit of the solar region after including the results of the second phase of SNO [22].

The near future accelerator experiments (MINOS, ICARUS, OPERA) should provide further constraints. After five years of data taking MINOS should reach the sensitivity of $0.06 - 0.08$ (depending on the systematic uncertainty). In the case of the CNGS experiments, the limiting factor is the ν_e contamination of the beam, hard to control without the near detector.

The further future dedicated experiments (in the first-stage aiming at a sensitivity of 0.01) can proceed in two ways: either by searching for the ν_e appearance in the $\nu_\mu \to \nu_e$ oscillations or by looking, á la CHOOZ, for the $\overline{\nu}_e$ flux suppression in a reactor disappearance-experiment.

The leading term in probability of the ν_e appearance in $\nu_\mu \to \nu_e$ oscillations is proportional to $\sin^2\theta_{13}$. Including also the term describing the dependence on the CP violating phase $\delta_{\rm CP}$, one gets approximately [36]

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$\pm\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{13}\sin\delta_{\rm CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta_{31} + \ldots\,, \quad (4)$$

where $\Delta_{31} = \frac{\Delta m^2_{31} L}{4E_\nu}$. Two observations are important here: the possibility to measure the CP violation in the leptonic sector depends on the value of $\sin 2\theta_{13}$, and the measurement of $\sin 2\theta_{13}$ itself depends on the other oscillation parameters (correlations) quadratically and trigonometrically (degeneracies). Thus, we have to measure $\sin 2\theta_{13}$ before deciding on the measurements of the CP violation and, in order to resolve the ambiguities, several measurements under different experimental conditions should be performed.

Two interesting experimental projects are considered: the NuMi off-axis [33] experiment at Fermilab and the JHF- (or equivalently J-PARC-) Kamioka neutrino project in Japan [34]. In the off-axis experiments the detector is located at a certain angle (of the order of a few tens of mrads) with respect to the beam direction. Due to the kinematics of the π decays, the off-axis neutrinos have a narrower energy spectrum, reflecting the pions' $p_{\rm T}$ distribution, while on-axis neutrinos have energies proportional to the pions' energies, which have a larger spread. This solution yields a considerable background reduction and better tuning of the neutrino energy to the first oscillation maximum.

Two phases are considered for both these projects — the second with very long time scales (2020 for NuMi), giant detectors (1 Mton Hyper-Kamiokande water detector) and very intensive beams (*e.g.* about 4 MW proton beam in J-PARC). The experimental challenges are enormous. *E.g.* the construction of a target supporting a 4 MW proton beam is far from trivial. After the first stage the $\sin^2\theta_{13}$ measurements should reach the sensitivity of the order of 0.01. The second stage should give a factor of ten improvement.

The complementary approach to the θ_{13} determination relies on a reactor disappearance experiment with the baseline corresponding to the atmospheric Δm^2_{23} (first proposed in [35]). A big advantage of this approach is that the survival probability for $\overline{\nu}_e$ directly measures $\sin^2 2\theta_{13}$ without parameter degeneracies [36]:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\Delta_{31} - \ldots\ . \quad (5)$$

The question is how much the new experiment would improve over the sensitivity of CHOOZ. At least two identical detectors (near and far) will be needed in order to reduce the error on the $\overline{\nu}_e$ flux. The detectors should be cross-calibrated. The idea of a movable experimental setup is also considered. According to [36] the sensitivity of 0.01 in $\sin^2 2\theta_{13}$ should be reached with this kind of experimental setup located at a single- or two-reactor site with an average thermal power of 3 GW per reactor. The authors of [37] get more conservative values, claimed to be more realistic, of 0.017 to 0.026.

4.4. CP violation and sign of Δm^2_{23}

If the determination of $\sin^2\theta_{13}$ is within the reach of the future off-axis and reactor experiments, studies of CP violation in the leptonic sector could start. The CP asymmetry in the $\nu_\mu - \nu_e$ channel, to leading order in the Δm^2-s, is given by the equation [1]

$$\frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} = -\left(\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin^2\theta_{23}}\right)\left(\frac{\sin 2\Delta_{12}}{\sin 2\theta_{13}}\right)\sin\delta_{\rm CP}\,. \tag{6}$$

Both the ν_μ and the $\overline{\nu}_\mu$ beams are needed for this measurement. Because the contribution of the sub-leading scale Δm^2_{12} enters the formula, large values of L/E are necessary to measure the asymmetry. Moreover, parameter degeneracies as well as matter effects in the Earth can hide the effect. In order to resolve them, combinations of measurements for different L/E and with different experimental setups will be needed [1].

Neutrino factories [38] can turn out to be the only adequate accelerators for measuring the CP violation. Conventional neutrino beams, even if super-beams, are formed by ν_μ (or $\overline{\nu}_\mu$) from the pion decays (with a ν_e ($\overline{\nu}_e$) contamination from kaon decays), while muons from the decays are absorbed. In the neutrino factories, muons will be captured and accelerated to the energy of 20–50 GeV. Then the beam will be put into a storage ring with long straight sections serving as decay tubes. Simultaneously produced pairs of ν_μ and $\overline{\nu}_e$ (or $\overline{\nu}_\mu$ and ν_e) will be ideal for studies of CP violation in the detectors located at a distance of the order of thousand or several thousands km (optimized according to L/E_ν and problems to be solved).

For such long distances as in the future LBL accelerator experiments the matter effects in the Earth can influence the oscillations. They can reveal, as in the case of solar neutrinos, the yet unknown sign of Δm^2_{23}.

5. Absolute neutrino mass

The oscillation experiments bring information about the differences of the masses squared. They cannot measure neutrino masses. Since the sign of Δm^2_{23} is unknown yet, two possibilities of the mass ordering exist. They are called normal and inverted mass hierarchies and are presented in figure 2. If the mass of the lightest neutrino is small, then the mass of the heaviest one is $\sqrt{|\Delta m_{23}^2|} \approx 40$ meV and either of these hierarchies can exist. If the lightest neutrino is heavy ($m \gg 40$ meV), the neutrino masses are quasi-degenerate.

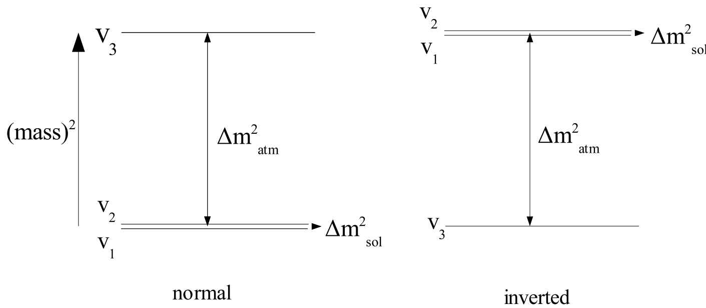

Fig. 2. Hierarchies of neutrino masses.

As discussed in the previous section, the determination of the sign of Δm_{23}^2 may come from future oscillation experiments. The absolute neutrino masses must be measured applying different methods. Three types of measurements are pursued: direct measurements of the end-point energy in tritium beta decay, cosmological estimates providing limits on the sum of masses of all the neutrino species and measurements based on lifetime determination for the neutrinoless double beta decays. In order to distinguish between the mass hierarchies and the case of quasi-degenerate neutrino masses the sensitivity of the mass measurements must be better than 40 meV.

The effective mass determined from the end-point region of the electron spectrum in ^{3}H beta-decay is $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$. The present limit $m_\beta \leq 2.2$ eV at the 2σ level comes from the Troitsk [39] and Mainz [40] experiments. A big collaboration including physicists from both experiments is working on the next-generation experiment KATRIN [41], which will start in 2007 and whose sensitivity should eventually reach 0.2 eV. In order to get this factor of ten improvement, the experiment will use a very strong ^{3}H source and a large electrostatic spectrometer with $\Delta E = 1$ eV, will take data during 1000 days and will have to reduce systematic errors by more than a factor of ten as compared to its predecessors.

The most stringent bound on the sum of neutrino masses comes from the recent cosmological measurements, the WMAP [42] Sky Map of the Cosmic Microwave Background and the 2dF Galaxy Redshift Survey [43]. Depending on the assumptions and selection of data sets, the analyses give slightly different results. However, they are consistent with an upper limit of 1 eV for the sum of neutrino masses.

5.1. Neutrinoless double beta decay

The third way of probing the absolute neutrino mass is by measuring half-lives $T^{0\nu}_{1/2}$ of the neutrinoless double beta decays ($\beta\beta 0\nu$), provided that the neutrinos are Majorana particles, *i.e.* that lepton number is not conserved and the neutrino is identical with its antineutrino. A recent summary concerning the double beta decays ($\beta\beta 0\nu$) is given in [44] (see also references there).

The ordinary double beta decays ($\beta\beta 2\nu$) correspond to rare but allowed transitions ${}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^- + 2\overline{\nu}$, which may happen when the binding energy of the intermediate nucleus ${}^A_{Z+1}X$ is lower than the binding energy of the nucleus ${}^A_Z X$. The transition, which corresponds to the $\beta\beta 0\nu$ decay is ${}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^-$ with the characteristic line corresponding to the sum of the electron energies at the end of the energy spectrum for the corresponding $\beta\beta 2\nu$ decay. A number of even-even nuclei decay via $\beta\beta 2\nu$, *e.g.* ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe, ^{160}Gd.

The effective mass $m_{\beta\beta}$ is related to the measured half-lives $T^{0\nu}_{1/2}$ and to a nuclear matrix element which is poorly known. For example, half-lives $T^{0\nu}_{1/2}$ calculated theoretically assuming $m_{\beta\beta} = 10$ meV and using various phenomenological models to calculate the nuclear matrix element differ by an order of magnitude (typically one obtains between 10^{28} and 10^{29} years). This corresponds to a factor of three uncertainty in the determination of $m_{\beta\beta}$ [44]. The current best upper limits on $m_{\beta\beta}$ come from the Heidelberg–Moscow [45] ($m_{\beta\beta} < 0.35$ eV) and the IGEX [46] ($m_{\beta\beta} < (0.33 - 1.35)$ eV) experiments.

The announcement of the discovery of the $\beta\beta 0\nu$ decay from a few members of the Heidelberg–Moscow Collaboration [47] requires further experimental confirmation. Several new experiments, exploiting very interesting techniques, are being prepared with a goal of reaching high sensitivity (for details see [44]). After fundamental discoveries in the domain of the neutrino oscillations, searches for neutrinoless double beta decays got a new boost. It is the only way to answer the question whether neutrinos are Dirac or Majorana particles.

6. Ultra high energy neutrinos

The primary goal of the studies of ultra high energy (UHE) neutrinos is the search for extraterrestrial, or even extragalactic, sources of the highest energy phenomena. For example, the cores of active galaxies (AGN) and gamma ray bursts (GRB) are currently considered candidates. Since neutrinos propagate undeflected from the source to the Earth, they bring information complementary to the knowledge based on photons or charged particles. In particular, high energy neutrino astronomy may help to resolve the mystery related to the mechanism for accelerating cosmic rays to energies above 10^{15} eV.

The rate of UHE neutrinos is very low, hence the detectors to register their interactions must be huge. The interesting technique, based on the detection of Cherenkov light with photomultipliers deployed in lake or sea water or in ice, is applied. The photomultipliers are settled on strings or towers with a typical distance between neighboring photomultipliers of a few tens of meters and at a depth of at least several hundreds meters. This technique has been pioneered by the DUMAND [48] and BAIKAL [49] experiments with relatively small detectors deployed in water and by the AMANDA experiment [52] with its 0.1 km^3 detector frozen into Antarctic ice close to the South Pole. The future IceCube detector, based on the same principles and located near the AMANDA detector, will have a volume of 1 km^3. At the stage of deploying prototype detectors in the Mediterranean sea are two water experiments ANTARES [50] and NESTOR [51]. It is worth to notice that the NESTOR detector will work at a depth of 4000 m and that according to the first measurements performed with the prototype detectors the background is due mostly to bioluminescence of fishes, bacterias *etc.* In order to avoid the background from cosmic muons AMANDA and IceCube are dedicated to the searches of UHE neutrino sources on the Northern Sky, while the water detectors will look at the Southern Sky.

The AMANDA collaboration analyzed the data taken in 1997 [53] and has recently reported on the data taken with the upgraded detector in 2000 [54]. No excess of events above those expected from the background atmospheric events has been observed yet, but the experiment has achieved the sensitivity required to probe known TeV γ-ray sources in the Northern hemisphere. It is worth to add that in the IceCube detector the charge current interactions of the tau neutrinos with energies in the PeV range, if only so energetic neutrinos exist, will be easily tagged through the well separated signals (typically at a distance of a few hundred meters) of the τ lepton itself and of its decay products.

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