Recent results in neutrino physics

L. Ludovici[a]

[a]University of Rome La Sapienza and INFN Roma
P.le A. Moro 2, 00185 Roma, Italy

The current status of neutrino physics is presented, with focus on the latest experimental results on neutrino masses and oscillation.

1. INTRODUCTION

Although the study of neutrino physics has led to many progresses in the understanding of elementary particles interactions, there are still many unknowns about the intrinsic properties of the neutrino itself. We do not know their masses and whether they are Dirac or Majorana particles. We do not know their magnetic moment. We know there are only three active neutrinos, with standard coupling with the Z boson, but we do not know whether sterile neutrinos (with no coupling to the Z) do exists and how many. In recent years the evidence for neutrino oscillation between different flavours has gained strenght with several very interesting experimental results. This implies that, unlike the assumptions of the Standard Model of the electroweak interactions, neutrino have non-degenerate, non-zero masses. If confirmed, this would represent a major revolution in our understanding of elementary particle physics.

In this paper the latest experimental results will be reviewed.

2. DIRECT MASS MEASUREMENTS AND DOUBLE BETA DECAY

The most recent experimental limits on neutrino masses obtained from direct kinematic searches are (at 95% C.L.): [1,2] [3] [4]

1. $\mathrm{m}_{\nu_\mathrm{e}} < 2.2$ eV; from tritium decay
2. $\mathrm{m}_{\nu_\mu} < 190$ KeV; from pion decay at rest
3. $\mathrm{m}_{\nu_\tau} < 15.5$ MeV; from tau hadronic decays

These limits hold for the flavour combinations $\mathrm{m}^2_{\nu_\mathrm{x}} = \Sigma_i |U_{xi}|^2 \mathrm{m_i}^2$, where no cancellations are possible between the neutrino mass eigenstates $\mathrm{m_i}$. Owing to the small mass differences given by the atmospheric and solar neutrino evidences for oscillation, the most stringent limit above allows to set the limit $\Sigma_i \mathrm{m}_{\nu_i} < 6.6$ eV, which applies to the sum of all neutrino masses. There are prospects to push down to less than 1 eV, 10 KeV and 3 MeV the sensitivities to respectively ν_e, ν_μ and ν_τ masses.

The double beta decay has been finally observed consistently with Standard Model predictions. Direct counting experiments searching for the lepton number violating, neutrinoless double beta decay produced up to now negative results. The lower limits obtained for the lifetime of this non Standard Model process, can be translated in upper limits on the combination $\langle \mathrm{m}_\nu \rangle = \Sigma_i U^2_{ei} \mathrm{m}_i$ of neutrino masses and mixings, where cancellations between non-zero neutrino masses m_i are possible. The present limit[5] $\langle \mathrm{m}_\nu \rangle \lessapprox 0.44$ eV appears difficult to be significantly improved, due to the uncertainty on the nuclear matrix elements. In the particular case of degenerate neutrino masses, the limits above set a constraint on the mixing angle combination $\Sigma_i U^2_{ei}$. It is worth to remark that the neutrino-less double beta decay is the best experimental probe to test the majorana nature of neutrino masses, which is of fundamental importance for the leptogenesis explaination of the matter anti-matter asymmetry.

3. THE SOLAR NEUTRINO OSCILLATION

After the first historical observation of the Homestake chlorine experiment, published in 1968 by R.Davis and collaborators [6], the deficit in the flux of neutrinos from the Sun has been confirmed by others radiochemical experiments using gallium: SAGE,[7] GALLEX[8] and its successor GNO[9]. The water-Cherenkov Kamiokande[10] experiment and its successor Super-Kamiokande[11] have also confirmed an experimental deficit with respect to the neutrino flux predicted by the Standard Solar Model (SSM) in absence of exotic phenomena like neutrino oscillation. Since the first chlorine experiment results, a number of solar models has been developed. They all make similar assumptions on the fundamental nuclear processes producing the solar energy and they use the known radius, mass, nuclear abundances and luminosity as constraints. The most famous and referenced model is certainly that of Bahcall-Pinsonnault. Its most recent versions, BP98[12] and BP2000[13], are used to interpret almost all latest experimental results. Other models give similar predictions[14].

The dominant source for the chlorine experiment are the ^{8}B neutrinos (76%) with smaller contributions from ^{7}Be (15%), pep and CNO neutrinos. The chlorine experiment detects electron neutrinos by extracting and counting the ^{37}Ar produced in a large volume of ^{37}Cl via the reaction $^{37}\mathrm{Cl}+\nu_\mathrm{e} \rightarrow {}^{37}\mathrm{Ar}+\mathrm{e}^-$, which has a threshold of 814 KeV. Gallium experiments are also sensitive to electron neutrinos via the reaction $^{71}\mathrm{Ga}+\nu_\mathrm{e} \rightarrow {}^{71}\mathrm{Ge}+\mathrm{e}^-$ wich has a lower threshold (233 KeV). Gallium experiments are the only sensitive to the pp neutrinos, by far the most abundant component of the solar neutrino flux.

Kamiokande and its successor Super-Kamiokande are large volume water-Cherenkov detectors located in the Kamioka mines in Japan. They are sensitive to all active neutrinos through the elastic scattering (ES) $\nu_\mathrm{x} + \mathrm{e}^- \rightarrow \nu_\mathrm{x} + \mathrm{e}^-$. The flux they measure is $\Phi_{ES}(\nu_\mathrm{x}) = \Phi(\nu_\mathrm{e}) + 1/6.5(\Phi(\nu_\tau) + \Phi(\nu_\mu))$, where the factor 6.5 comes from the ES cross-section ratio for ν_e and $\nu_{\mu\tau}$.

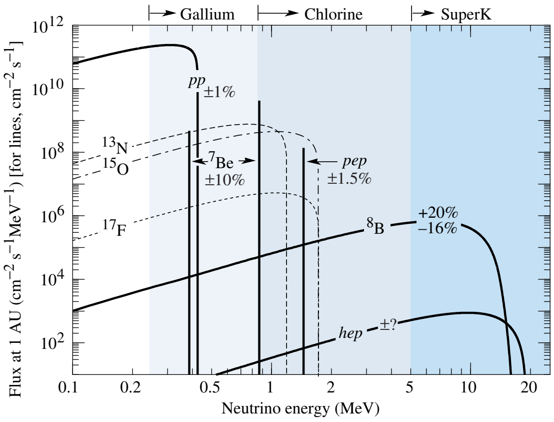

Figure 1. BP2000[13] predictions for the energy spectra of solar neutrinos. The continuum spectra are expressed in events cm^{-2}s^{-1}MeV^{-1} at one astronomical unit, while the monochromatic lines are given in events cm^{-2}s^{-1}.

Due to the relatively high threshold (5 MeV in Super-Kamiokande) these experiments are sensitive only to the ^{8}B neutrinos. On the other hand they are real-time experiments and the correlation between the incoming neutrino and the recoil electron, both in direction and energy, greatly improves the signal to background separation and allows a measurement of the energy spectrum. Moreover the night-time and day-time spectra can be compared, thus probing matter effects in the Earth.

In 1999 a new real-time experiment, SNO (Sudbury Neutrino Observatory) [15], started taking data. This experiment is a heavy-water($\mathrm{D_2O}$) Cherenkov detector located 2 Km underground in the Sudbury mine (Ontario, Canada). The experiment can detect ^{8}B neutrinos through three different reactions. The same elastic scattering reaction seen by the water-Cherenkov, the charged current (CC) reaction $\nu_\mathrm{e} + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ and the neutral current reaction $\nu_\mathrm{x} + \mathrm{d} \rightarrow \mathrm{n} + \mathrm{p} + \nu_\mathrm{x}$.

In table 1 is summarised the status of the solar neutrino flux measurements. All experiments see

Table 1
Comparison between the measured neutrino fluxes and the corresponding BP2000 predictions. In the last column theoretical and experimental errors are added in quadrature.

Experiment	Technique	Observed (SNU)	^{8}B (%)	^{7}Be (%)	pp (%)	others (%)	Observed/BP2000
Homestake	ν_e on ^{37}Cl	2.56 ± 0.23	76	15	–	9	0.34 ± 0.06
GALLEX	ν_e on ^{71}Ga	$77.5^{+7.5}_{-7.8}$	9	27	54	10	0.61 ± 0.07
GNO	ν_e on ^{71}Ga	$65.8^{+10.8}_{-10.3}$	9	27	54	10	0.51 ± 0.09
SAGE	ν_e on ^{71}Ga	$67.2^{+8.0}_{-7.6}$	9	27	54	10	0.53 ± 0.07
Experiment	Technique	Observed (10^6cm^{-2}s$^-1$)	^{8}B (%)	^{7}Be (%)	pp (%)	others (%)	Observed/BP2000
Kamiokande	ν_x ES in water	2.80 ± 0.38	98.5	–	–	1.5	$0.55^{+0.13}_{-0.11}$
Super-Kamiokande	ν_x ES in water	$2.32^{+0.09}_{-0.08}$	98.5	–	–	1.5	$0.46^{+0.09}_{-0.08}$
SNO	ν_x ES in D_2O	$2.39^{+0.38}_{-0.37}$	98.5	–	–	1.5	$0.47^{+0.12}_{-0.10}$
SNO	ν_e CC in D_2O	$1.75^{+0.15}_{-0.14}$	98.5	–	–	1.5	$0.35^{+0.07}_{-0.06}$

a flux deficit when compared to SSM calculations. Albeit hot discussions in the past decades, no convincing astrophisical explainations have been found to reconcile models and experiments. The inconsistency of the solar neutrino results in absence of neutrino oscillation is deeper than a simple normalisation problem. The major puzzle is that the water-Cherenkov rate suppression can be used to predict the suppression of the ^{8}B component in chlorine in a rather model independent way. The thresholds are different, but the water-Cherenkov data shows no spectral distortion and the shape of the expected ^{8}B flux is not very much dependent on the SSM parameters. Applying the suppression of the ^{8}B measured in water-Cherenkov the ^{8}B contribution alone already saturates the observed neutrino rate in chlorine. So the small but not negligeable contribution of non ^{8}B neutrinos (dominantly ^{7}Be) to the chlorine data should be negative. In other words, taken together, the chlorine and water-Cherenkov data suggest that there are no ^{7}Be neutrinos coming from the Sun. This is a real paradhox, because berillium is produced together with the ^{8}B neutrinos in the thermonuclear reaction $^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^\star + e^+\nu_e$. This fundamental correlation between ^{8}B and ^{7}Be makes almost impossible for a sensible solar model to account for this effect.

A second problem is that the neutrino rate measured in gallium experiments is completely saturated by the predicted pp neutrinos, which are the dominant component of the neutrino flux and are severely constrained up to 1% in all solar models. There is no room left for the additional contributions to the neutrino flux in gallium.

The single most dramatic evidence of new physics in table1 comes from a recent result from SNO [16]. The electron neutrino flux from the Sun, measured by the SNO experiment via the CC reaction, is inconsistent with the active neutrino flux measured by Super-Kamiokande via the ES reaction:

$$\Phi^{SK}_{ES}(\nu_x) - \Phi^{SNO}_{CC}(\nu_e) = (57 \pm 17) \cdot 10^4 \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad (1)$$

The active neutrino flux measured via the ES reaction by SNO, though compatible with the Kamiokande and Super-Kaniokande measurements, has yet a poor statistics to show a significative excess in the comparison with the CC flux. The equation above is by itself an evidence for the presence of non-ν_e active neutrino component in the solar neutrino flux. This result is independent from the neutrino flux calculation given by solar models. Neutrino oscillation is the natural explanation of this neutrino flavor conversion. Using the ratio of ES cross section for ν_e and $\nu_{\mu T}$, the results of eq. 1 can be used to measure the total flux of active ^{8}B neutrinos from the Sun $\Phi(\nu_x) = (5.44 \pm 0.99) \cdot 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is in very good agreement with SSM expectations.

This result plays a very important role because apparently there are no other manifestation of neutrino oscillation from the Sun which are flux independent. There is a negative result for a day-night asymmetry in the solar neutrino flux, which would be an evidence of matter effects in the neutrino propagation in the Earth. Moreover the neutrino flux as a function of the solar zenith angle is rather flat and does not show any of the features expected from matter effect. Also negative is the search for distortion of the neutrino energy spectrum. The ^{8}B neutrino spectrum is measured by Kamiokande and Super-Kamiokande through the measurement of the recoil electron momentum and its shape shows no evidence for distortion with respect to the non-oscillated spectrum. Incidentally Super-Kamiokande has excluded a large non-standard contribution from hep neutrino to the observed ^{8}B spectrum. The hep contribution to the observed flux has been measured to be smaller than $4 \cdot 10^4 \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 90% CL and then hep neutrinos contribute negligeably as expected from SSM calculations. Finally no seasonal effects have been observed on top of the expected flux modulation due to the eccentricity of the Earth orbit around the Sun. Altough no astrophysical explanation was found for the solar neutrino deficit, the result in eq.1 above stand as the only flux independent evidence (and likely the first smoking-gun) for solar neutrino oscillation.

A number of authors have presented global analyses of solar neutrino data, too many to be aknowledged here. Figure 2, shows the allowed oscillation parameters regions according to reference [17]. Most of this global analyses uses the neutrino event rates from chlorine and gallium experiments, the CC event rate from SNO and the Super-Kamiokande day and night spectra separately. Experimental results are compared with the BP2000 SSM calculations. There are several features common to almost all global analysis, though sometime the conclusions depend on details of assumptions on the solar model and on the analysis procedure.

- a relatively large sterile component in a transition $\nu_e \to \cos\eta \cdot \nu_{\mu\tau} + \sin\eta \cdot \nu_s$ is still compatible with present data;
- a pure transition to sterile neutrinos ($\eta =$ 90° above) is excluded at 99% C.L.;
- the LMA solution ($\Delta m^2 \approx 4.2 \cdot 10^{-5}$ eV^2,$\tan^2\theta \approx 0.26$) is most favored;
- the LOW ($\Delta m^2 \approx 7.6 \cdot 10^{-8}$ eV^2,$\tan^2\theta \approx 0.72$) and VAC ($\Delta m^2 \approx 1.4 \cdot 10^{-10}$ eV^2,$\tan^2\theta \approx 0.38$) give acceptable fits;
- the SMA ($\Delta m^2 \approx 5.2 \cdot 10^{-6}$ eV^2,$\tan^2\theta \approx 5.5 \cdot 10^{-4}$) gives significantly less good fit;
- other solutions give poor fit results.

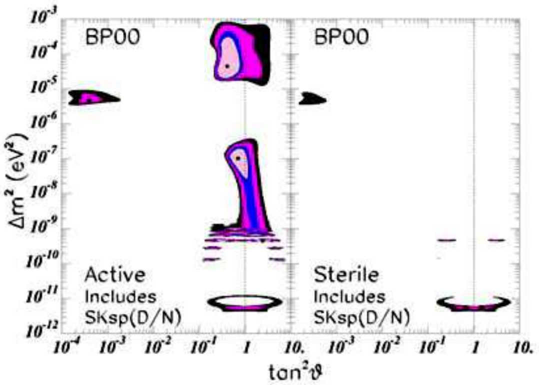

Figure 2. Allowed parameter regions for solar neutrino oscillation into pure active (left) and pure sterile (right) neutrinos (from ref. [17]).

The favored solutions (LMA, LOW and VAC) are characterised by small mass differences (in the range $10^{-5} - 10^{-2}$ eV) and large mixing angles.

KAMLAND [18], a reactor experiment which is presently starting data taking in Japan, will measure the electron neutrinos coming from all japanese reactors. The large effective baseline will make possibile to fully explore the LMA solution of solar neutrino oscillation in a controlled artifical source. If KAMLAND will detect the electron neutrino disappearance, it will be able in a few years to measure Δm^2 at 2% and $\sin^2 2\theta$ at 4%.

Borexino [19], an ultra-pure liquid scintillator experiment in the Gran-Sasso laboratory, in Italy, is expected to be operational in a few months. It has a similar design with KAMLAND, with the major difference being the unprecendented Borexino requirement in scintillator purity. Its aim is to achieve threshold low enough to pin down the monochromatic ^{7}Be line of the solar neutrino spectrum. The measurement of day-night asymmetry and seasonal variation of the ^{7}Be flux will distinguish between different allowed parameter regions for solar neutrino oscillation.

4. THE ATMOSPHERIC NEUTRINO OSCILLATION

Neutrinos are produced in the Earth's atmosphere from the decay of muons and pions created in the interaction of primary cosmic rays (80% protons, 15% α particles, 5% heavier nuclei). The interaction of primary cosmic rays produces pions which decay into a muon and a ν_μ (or $\bar{\nu}_\mu$ for negative charge pions). Each muon, if its energy is not larger than about 2 GeV, decays before reaching the Earth's surface, producing a $\bar{\nu}_\mu$ and a ν_e (or ν_μ and $\bar{\nu}_e$). So the ratio $\mathcal{R}$ of muon neutrinos to electron neutrinos is expected to be rather independent from the details of the theoretical models and $\mathcal{R} \approx 2$ is expected if there are no effects, like neutrino oscillation, able to change the neutrino flavour composition. Most of the time it is quoted the double ratio $\mathcal{R}' = \mathcal{R}_{DATA}/\mathcal{R}_{MC}$, where $\mathcal{R}_{DATA}$ is the experimental ratio of muon-like events (i.e. charged current interactions of ν_μ or $\bar{\nu}_\mu$) to electron-like events (same for ν_e or $\bar{\nu}_e$) and $\mathcal{R}_{MC}$ is the same ratio obtained from a Monte Carlo simulation, taking into account detector acceptances.

In 1986 IMB (a water Cherenkov detector in the USA) and two years later Kamiokande reported an anomalous ratio $\mathcal{R}'$ of about 0.6. The debate of this so-called atmospheric neutrino anomaly has continued for about a decade. NUSEX and Frejus, two fine-grained iron calorimeters, although not conclusively incompatible with the previous result, did not confirm the anomalous ratio. On the contrary Soudan2, a fine-grained iron calorimeter in the USA, did confirm the anomaly. The big boost of the scientific community's consensus on the evidence for oscillation of atmospheric neutrinos, came with the Super-Kamiokande result in 1998.

The most recent value of $\mathcal{R}'$ reported by Super-Kamiokande, based on 1289 days of data, is $0.638 \pm 0.017 \pm 0.050$, about 7σ away from unity. But the single most convincing evidence in favour of neutrino oscillation is given by the zenith angle distributions of muon-like and electron-like events which is show in fig. 3. The electron-like events

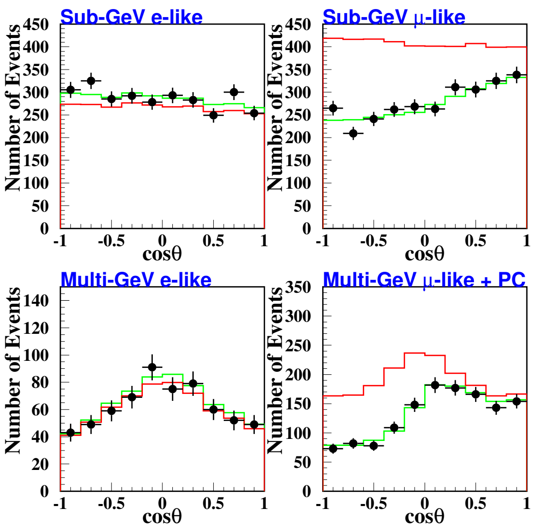

Figure 3. Super-Kamiokande zenith angle distribution for the samples of electron-like and muon-like events where a single Cherenkov ring is detected.[22] Sub-Gev and Multi-GeV refers to energy below and above 1.33 GeV. The solid line is the expectation in absence of oscillation. The hatched line is for $\nu_\mu \to \nu_\tau$ with maximal mixing and $\sin^2 2\theta = 2.5 \cdot 10^{-3}\mathrm{eV}^2$.

agree with expectation well within the 25% systematic uncertainty on the atmospheric neutrino flux calculations. On the contrary the muon-like events strongly disagree with the expectation in absence of oscillation. The zenith distribution for multi-GeV muon neutrinos coming from above

($\cos\Theta > 0$) is only mildly distorted, while the deficit is maximum for neutrinos coming from below. This is consistent with ν_μ oscillation occuring with a Δm^2 matched by a baseline larger than the path traveled by downward-going neutrinos. Downward-going neutrinos travel $10 \div 20$ km, while upward-going neutrinos, produced at the opposite side of the Earth, travelled about $12,000$ km. The study of the atmospheric zenith distribution is a tool which give access to three orders of magnitude in oscillation baseline, by far more than the reach of long baseline accelerator experiments.

The up-down asymmetry of muon-like events is largely independent from uncertainty in the absolute flux normalisation and presently stands as the single most convincing evidence for oscillation of atmospheric neutrinos. Super-Kamiokande extracted the allowed parameter region for $\nu_\mu \to \nu_\tau$ oscillation, from a multi-dimensional likelihood fit to the energy and zenith angle distributions for all the available data (fully contained event as well as partially contained, through-going muons and multi-ring events). The best fit after 1289 days of data taking corresponds to maximal mixing and $\Delta m^2 = 2.4 \cdot 10^{-3}$ eV^2. The allowed region at 90% C.L. covers the range $\Delta m^2 = 1.3 \div 5 \cdot 10^{-3}$ eV^2, with almost maximal mixing ($\sin^2 2\theta > 0.88$).

The parameter space region relevant for oscillation of atmospheric neutrinos has been explored also by the CHOOZ and Palo Verde reactor experiments, looking for ν_e disappearance. Their limits exclude oscillation to ν_e as a possible channel for the ν_μ disappearance observed by Super-Kamiokande, at least as a dominant mode. Super-Kamiokande has tested both the oscillation hypothesis $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$. Oscillation into sterile neutrinos would show up with a depletion and an up-down asymmetry for NC events, because the sterile neutrino has no coupling with the Z. Another handle are the different matter effects expected for oscillation into ν_τ and ν_s, which are better visible in the higher energy samples of upward passing-through muons and partially contained events. From a combined analysis of all these samples, Super-Kamiokande excluded at 99% C.L. oscillation into pure sterile neutrinos. As in the solar case, oscillation into a state with a relatively large sterile component cannot be excluded yet. Within the Super-Kamiokande particle identification capabilities, direct tau appearance can be observed looking to an excess of multi-ring π° events. A positive indication with a 2σ significance has been reported.

The 1998 Super-Kamiokande claim for atmospheric neutrino oscillation has promoted the "atmospheric neutrino anomaly" to a convincing evidence for neutrino oscillation, with $\nu_\mu \to \nu_\tau$ as the dominant channel. This has been afterword supported, though with less sensitivity, by Soudan2 [20] and MACRO [21]. Atmospheric neutrinos, with the opportunity they offer to access a large range of oscillation baselines, will remain an important experimental battlefield to firmly establish the oscillation phenomenon. At the same time it is very important to test the same oscillation parameter region in controlled experimental conditions with an accelerator neutrino beam. To match the atmospheric neutrino Δm^2 , at the typical energies of neutrino beams ($1 \div 30$ GeV), the detectors must be located at a distance of several hundreds of kilometers.

The first long baseline accelerator experiment ever built has started data taking in June 1999 in Japan. In the K2K [23] experiment (KEK-to-Kamioka) a muon neutrino beam is produced by a 12 GeV proto-syncrotron at KEK and neutrino interactions are detected in the Super-Kamiokande detector, located about 250 km away. With an average neutrino energy of 1.3 GeV the experiment is looking for ν_μ disappearance with a maximum sensitivity at $\Delta m^2 \approx 5 \cdot 10^{-3}$ eV^2. This requires a reliable measurement of the neutrino beam intensity at the production and a careful extrapolation to the Super-Kamiokande location. The key is an additional detector, located at 300 m from the source, built as a small replica of Super-Kamiolande, using the same design and technology. With $3.9 \cdot 10^{19}$ proton on target, 44 events have been observed in Super-Kamiokande while $63.9^{+6.1}_{-6.6}$ where expected in absence of oscillation. The deficit has a significancy of about 2σ. The K2K collaboration has been very careful, waiting for more statistic and the release of the energy spectrum before giving an interpretation of this deficit in term of muon neutrino oscillation. With the present statistic the systematic error is still smaller than the poisson fluctuations. It is largely dominated by the uncertainty in the near-to-far extrapolation. Other sources like the uncertanty on the beam spectrum and on the neutrino cross-sections are negligible due to first order cancellations in the near-to-far comparison.

Long-baseline experiments are planned in Europe, OPERA [24] and ICARUS [25] at Gran Sasso, using the CNGS neutrino beam from CERN and MINOS [26] in the Soudan mine, using the NuMI neutrino beam from Fermilab. Both facilities have similar beams and baselines but different detection strategy, with the CNGS focussing on ν_τ appearance and NuMI on ν_μ disappearance.

5. NEUTRINO ASTROPHYSICS

The detection of high energy neutrino from astrophysical sources plays a key role in hot scientific issues like the acceleration mechanism for the Ultra-High-Energy Cosmic Rays above the GZK cutoff [27], the origin of Gamma Ray Bursts, the Active Galactic Nuclei and the detection of supernova bursts. The aim of the scientific community is to build one km^3 instrumented detector or hopefully one in the North hemisphere and one in the South hemisphere. Two major steps undertaken in this direction are ANTARES [28], a large detector under construction with photomultiplier strings deployed in the mediterranean sea, and AMANDA [29]. In its present status, AMANDA consists of photomultiplier strings deployed in the Antarctic ice sheet at the geographic South Pole, about 2km below the surface. The experiment has shown its capability to extract, from the large background of atmospheric muons, the signal of atmospheric neutrinos detecting upward-going muons from ν_μ charged current interactions. While the spectrum of atmospheric neutrinos falls steeply with increasing energy, neutrinos from astrophysical sources extend to higher energies. A limit $E_\nu^2 dN/dE_\nu = 0.9 \cdot 10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1} sr^{-1}\mathrm{GeV}$ at 90% C.L. is set on the diffuse flux of high energy neutrinos with a (E_ν^{-2}) power law. This limit is already in the range of the predictions from different models for AGN (Active Galactic Nuclei) and on the theoretical bounds existing for the diffuse flux of astrophysical neutrinos. For point-like neutrino sources the limit on the flux for an E_ν^{-2} power low spectrum is $\Phi(E_\mu > 10\ \mathrm{GeV}) = 0.6 \cdot 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the vertical direction and about an order of magnitude higher for the horizontal direction.

6. CONCLUSIONS

Solar and atmospheric neutrino experiments suggest that oscillation occurs with two dominant large mixing angles and two small and hierarchically separated mass scale differences $\Delta\mathrm{m}^2\odot \leq 10^{-4}\mathrm{eV}^2 \ll \Delta\mathrm{m}^2_{atm} \approx 10^{-3}\mathrm{eV}^2$. This implies that one neutrino mass eigenstate, say ν_3 has a large mass gap ($10^{-3}\mathrm{eV}^2$) with respect to two quasi-degenerate ($\leq 10^{-4}\mathrm{eV}^2$) mass eigenstates ν_1 and ν_2. Present atmospheric neutrino experiments do not measure the sign of the large mass gap $\Delta\mathrm{m}^2_{13}$ and so we can not discriminate the two hierarchies $\mathrm{m}_1 \approx \mathrm{m}_2 \ll \mathrm{m}_3$ and $\mathrm{m}_3 \ll \mathrm{m}_1\ \mathrm{m}_2$. Due to this hierarchy the solar and atmospheric neutrino oscillations are almost decoupled as it can be shown that solar (atmospheric) neutrino oscillation are described by only three parameters: $\Delta\mathrm{m}^2_{21}$ ($\Delta\mathrm{m}^2_{32}$),θ_{12} (θ_{23})and θ_{13}. The subdominant angle θ_{13} connects these two oscillation phenomena that, in the limit $\theta_{13} = 0$ would decouple into two independent two-flavour oscillations. The only knowledge we have on this angle is the limit $\theta_{13} < 12°$, coming from CHOOZ [30].

In this emerging picture, with three neutrino oscillation, only two mass scales can be accomodated. It is worth to mention that an accelerator experiment, LSND, has reported appearance of ν_e in a ν_μ beam [31]. This result has not been neither confirmed nor disproved yet by other experiments. The MiniBOONE [32] experiment at Fermilab, in a few years should definitively check this result. A third mass scale, taking into account the number of active neutrinos measured at LEP, would demand for a fourth sterile neutrino. If LSND is discarded, mixing with a fourth sterile neutrino is not needed to explain the experimental results, but it is still compatible with them.

There are strong evidences that oscillation occurs and neutrino have masses. The underway medium term experimental neutrino programme, will likely strenghten the present picture with the observation of convincing oscillation patterns (a full oscillation cycle, tau appearance, NC appearance), solving the sterile neutrino question, improving the precision on the oscillation parameters, confirming the present results and ruling out alternative exhotic [33] explanations proposed.

The issues of θ_{13} and the CP violation in the leptonic sector call for a next round of experimentation with ambitious projects like the Neutrino Factory [34] and high intensity neutrino beams (*superbeams*) [35].

Whatever serendipitous surprise the future will give us, there is no doubt it is a fascinating time for neutrino physics.

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