Neutrino Physics and Astrophysics *

Michel SPIRO and Daniel VIGNAUD [a]

[a]DAPNIA/SPP, CEA/Saclay
91191 Gif-sur-Yvette, France

Neutrinos have been and are abundantly produced in the Universe and by accelerators or nuclear reactors. They play a key-role both in particle physics and in astrophysics. We focus in this review on the present quest for neutrino masses, mainly via the search for neutrino oscillations in the study of solar neutrinos, atmospheric neutrinos, and of neutrinos from accelerators or reactors.

1. INTRODUCTION

Invented by Pauli in 1930, named by Fermi in 1933 and discovered by Reines and and Cowan in 1956, neutrinos are still very puzzling particles. They play a key-role both in particle physics and in astrophysics. The LEP experiments have fixed the number of light neutrinos to 3 (a recent updated value is $n_\nu = 2.994 \pm 0.012$ [1]) and consequently the number of families (generations) of quarks and leptons to 3. The three neutrinos ν_e , ν_μ and ν_τ are associated to the three leptons e, μ and τ.

The precision tests performed by the LEP experiments have also strongly demonstrated the robustness of the so-called minimal standard model of particle physics. In this minimal standard model, the neutrinos are massless and left handed. However, all the other fermions (i.e. quarks and other leptons) are massive and, beyond the existing physics arguments, a simple æsthetical principle states that there is no reason why this should be different for neutrinos. In this respect, massive neutrinos are an important test to go beyond the minimal standard model (in spite of its success we know that it does not answer to several fundamental questions among which the fermion mass problem), a key to open the window towards grand unified theories (GUTs).

In simple grand unified theories (GUTs), there is a relation between the neutrino mass and the mass of the associated quark. A typical see-saw relation (see for example [2]) is :

$$m(\nu_i) = m^2(q_i)/M_U \;\Rightarrow\; m(\nu_e)/m(\nu_\mu)/m(\nu_\tau) \propto m_u^2/m_c^2/m_t^2 \qquad (1)$$

where M_U is the grand unification scale (10^{15} – 10^{16} GeV). There are other possible see-saw relations between the neutrino masses and the quark masses in these theories. Such a relation implies the typical following scale between neutrino masses :

*Plenary talk by Michel SPIRO at INPC98 (International Nuclear Physics Conference) - Paris, August 24-28 1998

$m(\nu_e)/m(\nu_\mu)/m(\nu_\tau) \approx 10^{-6}/10^{-3}/1$. Details on the main particle models on neutrino masses can be found for example in reference [3].

Massive or not, neutrinos have also strong implications in cosmology and astrophysics : they could contribute significantly (if massive) to the dark matter of the Universe (see for example [4]) ; the detection of cosmological neutrinos (a real challenge) would be very important with respect to the big bang theory ; solar neutrinos probe the core of the Sun and prove that nuclear reactions make the stars shine ; last but not least, neutrinos are not only witnesses in supernovæ explosions but also probably actors.

Neutrino astronomy extends from few meV for cosmological neutrinos (with fluxes as large as 10^{20} $cm^{-2}\,s^{-1}\,MeV^{-1}$) to probably 10^{20} eV for neutrinos coming from AGN (with fluxes smaller than 10^{-12} $cm^{-2}\,s^{-1}\,MeV^{-1}$). Figure 1 illustrates the spectrum of the different sources.

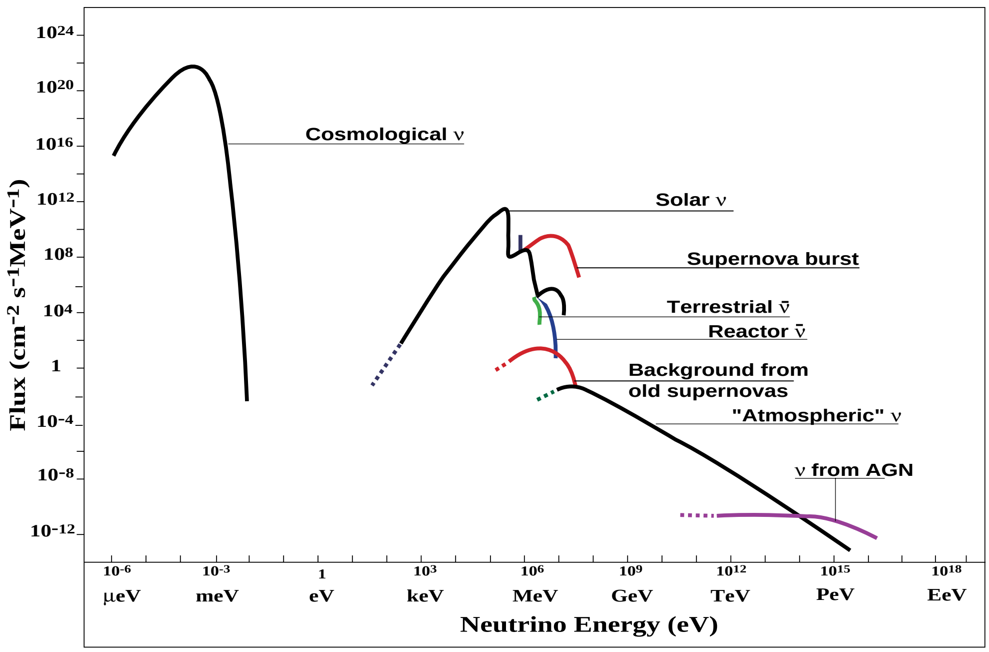

Figure 1. Energy spectrum of the different astronomical (or terrestrial) sources of neutrinos (from [5]).

Cosmological neutrinos will be briefly presented in section 2. Section 3 will address the question of the neutrino mass ; this mass, if non zero, is very small ; direct measurements have failed until now, as well as indirect measurements via double beta decays which also test the nature (Dirac or Majorana) of the neutrino ; ν oscillations are a powerful tool and their formalism is briefly described. The following sections describe the different experiments dealing with neutrino oscillations : solar neutrinos (section 4), reactor neutrinos (section 5), accelerator neutrinos (section 6), atmospheric neutrinos (section 7). Sections 8 and 9 will summarize the perspectives.

2. COSMOLOGICAL NEUTRINOS

Neutrinos relics from the big bang are the first fossils in the Universe. In the standard big bang theory, they decoupled only one second after the "so-called t=0". Their temperature is only 1.9 K (they are colder than the cosmic microwave background) and their mean energy about 0.5 meV (read "meV" not "MeV"). Each cm^3 of the Universe contains about 50 neutrinos of each species and the same number of antineutrinos, i.e. 300 in total. If they are massive, they could then contribute significantly to the missing mass of the Universe (see [4,6]).

Their detection would seriously confort the big bang theory. Difficulties come from their very small cross section (10^{-62} cm^2 if their mass is zero, slightly more if they are massive, 10^{-54} cm^2 for m_ν=10 eV). Almost all the proposals ("gedanken experiments" until now) suggest that relic neutrinos could be detected by the energy, momentum or angular momentum transferred during their coherent interaction with matter. The basic idea (see for example Langacker et al. [7]) is that their wavelength (few mm) is large compared to the interatomic spacing and the effect of the medium can be described via a refraction index in the propagation equation. The expected coherent effects are very small ($O(G_F^2)$ and not $O(G_F)$) [8], complicated by the fact that the flux is isotropic, and no serious proposal has been made (see also the idea developed by J. Dias de Deus and M. Pimenta to use Rydberg atoms to detect them [9]). Their detection is still a real challenge.

3. NEUTRINO PROPERTIES (IS ν MASSIVE ?)

The neutrino is a fermion (spin 1/2) with a null charge and interacts only by weak interaction with a very small cross section. Its mass is not known and there is an important property of the neutrino which is still puzzling : is the neutrino a Majorana or Dirac particle, i.e. is it or is it not its own antiparticle ? (We do not consider here the magnetic moment of the neutrino nor the possibility that neutrinos could decay).

There are three main ways to look for massive neutrinos : a) direct measurements of the mass ; b) double beta decay experiments (observation of double beta decay without neutrino emission would prove that neutrinos are massive and that they are of the Majorana type, i.e. that neutrinos are identical to antineutrinos) ; c) neutrino oscillations (either particle physics experiments close to accelerators or nuclear reactors, or astrophysics experiments like solar neutrino or atmospheric neutrino experiments can test this mechanism authorized by quantum mechanics).

3.1. Direct measurements of neutrino masses

Needless to say, we have only upper limits on the neutrino masses. Direct measurements use kinematic decay of particles which decay into ν_e , ν_μ or ν_τ .

Most of the results on direct measurements of the ν_e mass come from tritium decay ($^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$). The electron spectrum is measured using dedicated spectrometers, particularly close to the endpoint (18 600 eV) where a deviation from the expected spectrum would be indicative of a possible mass for the ν_e ; the difficulty is that the counting rate is very small and that a precision better that 1 eV is needed. Two experiments, one in Mainz (Germany) [10], and the other in Troitsk (Russia) [11] recently improved previous limits ($m(\nu_e) < 5.6\,$eV for Mainz and 3.5 eV for Troitsk) (see figure 2 for an illustration). There is however a problem : all the experiments report a negative value as the result of their fit for m_ν^2, and the weighted world average is -27 ± 20 eV^2 [1] . One cannot exclude systematic effects which have not yet been identified and/or understood, and the limit extracted from the fit could be too low.

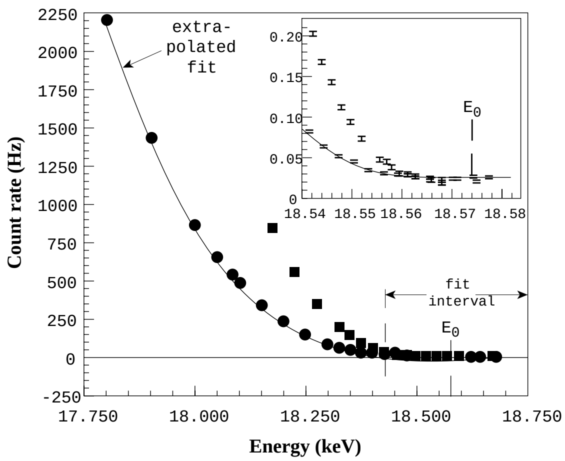

Figure 2. Energy spectrum of the Mainz tritium β-decay experiment close to the endpoint [10]. The line is the fit to the data. The insert shows the expected fit for different ν masses.

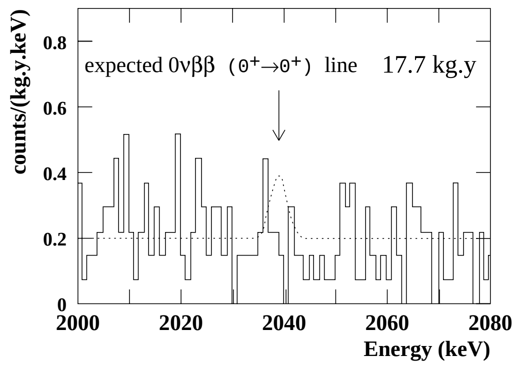

Figure 3. Energy spectrum observed by the Heidelberg-Moscow experiment after 17.17 kg.y measuring time [12].

An indirect limit on $m(\nu_e)$ comes from the neutrinos from SN1987A which travelled for 150 000 years and were detected in a few seconds. The time dispersion of the emitted pulse caused by a non zero ν mass can be written :

$$\Delta t \;=\; 0.026\,(d/50\,\mathrm{kpc})\,(m_\nu/1\,\mathrm{eV})^2\,(E_\nu/10\,\mathrm{MeV})^{-2} \qquad (2)$$

Though values as low as 10 eV have been quoted, it is considered that the realistic limit is $m(\nu_e) \lesssim 20\,$eV (see for example [13]).

The upper limit on the ν_μ mass has been recently improved at the PSI (Switzerland), using the decay $\pi^+ \rightarrow \mu^+\nu_\mu$ at rest and a precise measurement of p_μ. It is now $m(\nu_\mu) < 170\,$keV [14], but there is little hope to improve by an order of magnitude in the forthcoming years.

The best limit from the ν_τ mass comes from the ALEPH experiment which looks for the decay of the τ into $5\pi\nu_\tau$ and gives now $m(\nu_\tau) < 18.2\,$MeV [15].

These limits obtained in laboratory are still much higher (except for ν_e) than the cosmological bound that follows from avoiding the overabundance of relic neutrinos :

$$m(\nu_i) \;\leq\; 30\,\mathrm{eV} \qquad \text{for any of the known families.} \qquad (3)$$

This value slightly depends on the Hubble constant, and more details can be found in reference [6]. In reality, the situation is a little more complicated : cosmological constraints apply in the plane ν lifetime versus ν mass [6].

3.2. Double beta decay experiments

Double beta decay of a nucleus X can be written :

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-} \; (+\, 2\,\bar{\nu}_{e}) \tag{4} $$

Double beta decays with emission of two neutrinos ($\beta\beta 2\nu$), though very rare, are allowed processes (conventional second order weak process). There are 35 potential $\beta\beta$ emitters, on which 9 have been observed (^{48}Ca,^{76}Ge,^{82}Se,^{100}Mo,...), with half-lives going from 10^{19} to 10^{24} years.

Double beta decays without emission of neutrinos ($\beta\beta 0\nu$) are allowed only if neutrinos are massive and if they are Majorana particles (i.e. if the neutrino is its own antiparticle : $\nu = \bar{\nu}$). They have not yet been observed and are a powerful probe of particle physics beyond the standard model. The observation of such a process would imply the following relation between the effective mass of the neutrino and the half-life of the process $T^{0\nu}_{1/2}$:

$$ < m_{\nu} >^{2} = \; G^{0\nu} \, |M^{0\nu}|^{2} \, / \, T^{0\nu}_{1/2} \tag{5} $$

where $M^{0\nu}$ is the matrix element of the process.

The experimental effort is intense. It consists in identifying a line in the spectrum of the sum of the energy of the two electrons (since no neutrino is leaving, the kinematics of the decay is very simple); the requests are then a good energy resolution and a good background rejection. The new generation of experiments uses large sources of enriched materials, and considers different techniques : pure calorimetry (use of germanium crystals), tracking of electrons (use of TPC's) eventually followed by calorimetry (in the forthcoming NEMO 3 detector), cryogenic detectors (bolometers). The best limit on the $\beta\beta 0\nu$ decay comes from the Heidelberg-Moscow experiment, which uses about 19 kg of germanium enriched in ^{76}Ge in the underground Gran Sasso laboratory. The present result is $T^{0\nu}_{1/2} > 1.1\,10^{25}$ y [16] (see figure 3), inducing a limit of 0.46 eV (90 % c.l.) on $< m_{\nu} >$. Several years of running should give a limit of 0.1 eV. The NEMO 3 detector [17] (10 kg of foils of ^{100}Mo) should reach a similar limit, and it looks difficult today to reach a lower limit. As a dream, some people look for one ton of ^{136}Xe in a TPC which could give 0.01 eV in 5 years.

A more complete overview (theoretical and experimental) of the double beta decay physics can be found for example in reference [12].

3.3. How neutrinos can oscillate ?

Since the mid-seventies neutrino oscillations have been searched using either accelerators or nuclear reactors. We just briefly review here the formalism and will present the experiments in the following sections.

For massive neutrinos, the mass eigenstates ν_1 , ν_2 and ν_3 are in general different from the flavour eigenstates ν_e , ν_μ and ν_τ . The transformation between the flavour and the mass eigenstates is made through a 3×3 unitary matrix. In the simple case where we consider only two flavours, the transformation has only one parameter, θ, which is called the mixing angle, and is written :

$$ \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \tag{6} $$

Assuming ν_e propagating in vacuum, we have after a propagation time t : $\nu_e(t) = \cos\theta \exp(-iE_1 t)\nu_1 + \sin\theta \exp(-iE_2 t)\nu_2 \neq \nu_e$ (with $E_i = \sqrt{p^2 + m_i^2}$). The probability to observe a ν_e after a distance L=ct is :

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \times \sin^2(\pi L/L_v) \tag{7}$$

$L_v = 4\pi E/\Delta m^2$ is the vacuum oscillation length which depends on the neutrino energy E and on $\Delta m^2 = m_2^2 - m_1^2$, the difference of the squared mass of ν_2 and ν_1 . If E is in MeV and Δm^2 in eV^2, $L_v(m) = 2.5\,E/\Delta m^2$.

The parameters of neutrino oscillations are then the mixing angle θ and Δm^2 (for three families, we have three mixing angles and two Δm_{ij}^2). The purpose of all the experiments is to explore the (Δm^2, $\sin^2 2\theta$) plane , playing with the energy of the neutrinos and the distance between the source and the detector. Neutrinos from accelerators explore large Δm^2 (above $\gtrsim 1\,eV^2$ for present experiments where L is about 1 km, smaller values for long baseline experiments which are planned at distances of about 1 000 km) ; neutrinos from reactors (short distances but small energies) and atmospheric neutrinos explore between 10^{-3} and $1\,eV^2$; solar neutrinos can go to 10^{-11} eV^2. Starting from a given source (for example ν_e in the Sun or ν_μ in accelerators), there are two types of experiments : appearance experiments which search for example for a ν_μ or a ν_τ in a ν_e beam, and disappearance experiments which look for a deficit of a species ν_i compared to the expected flux.

The presence of matter can modify the propagation of neutrinos, since the mass eigenstates are no longer the propagation eigenstates. For some conditions on the density of the matter (a sufficient amount and a slow variation), a ν_e can be adiabatically transformed into a ν_2 . This property, discovered by Mikheyev, Smirnov and Wolfenstein and called the MSW effect [18], could explain the observed deficit of solar neutrinos as will be seen later.

4. SOLAR NEUTRINOS

In the core of the Sun, the temperature is sufficiently high (about 15×10^6 K) to initiate the hydrogen burning with the important primary fusion reaction between two protons : $p + p \to {}^2H + e^+ + \nu_e$ which produces the so-called pp-neutrinos, or ν_{pp}. Then follows a complicated sequence of nuclear reactions which produce in particular neutrinos from Be (called ν_{Be}) and neutrinos from B (ν_B). All these reactions can be summarized by a single one in which four protons combine into a ^4He nucleus :

$$4p + 2e^- \to {}^4He + 2\nu_e + 27\,MeV \tag{8}$$

This cycle of reactions is called the pp cycle and produces about 98 % of the energy of the Sun. The remaining is due to the CNO cycle which plays an important role in more massive stars where the central temperature is higher (this cycle uses C, N, O as catalysts to convert also 4 protons into helium and produce also neutrinos called ν_N and ν_O).

The modelling of the solar interior consists of describing the evolution of the Sun from its formation, about 4.6 Gyr ago, to the present day. Following the pioneering work of Bahcall [19], solar models called "standard" use the most simple physical hypotheses and the best available input physics. It is assumed that energy is generated by nuclear reactions in the core of the star ($r <\approx 0.25\,R_\odot$), and is transported by radiation in the central part and by convection in the outer part ($r > \approx 0.7\,R_\odot$). The basic evolution equation is the hydrostatic equilibrium between the outward radiative pressure force and the downward gravitational force.

The model calculation must reproduce some important parameters of the Sun as its mass (2×10^{33} g), its luminosity ($L_\odot = 3.8 \times 10^{26}$ W) and its radius (700 000 km), but also to account for the helioseismological measurements which can be characterized at first order by a single parameter, the sound velocity in the solar interior (derived by inverting measurements of the p-mode oscillation frequencies) [2].

Many solar models have been built in the past years. Most of the different codes are now validated since similar results are obtained when using the same inputs for nuclear cross sections, opacities, equation of state. Among the improvements we should quote the introduction of element diffusion processes (the stronger pull of gravity on helium and heavy elements caused them to diffuse slowly toward the solar center relative to hydrogen) [3] and the treatment of screening (the plasma polarization due to free electrons clustering around ions lowers the repulsive Coulomb barrier, and the nuclear reaction rates are enhanced by a so-called screening factor).

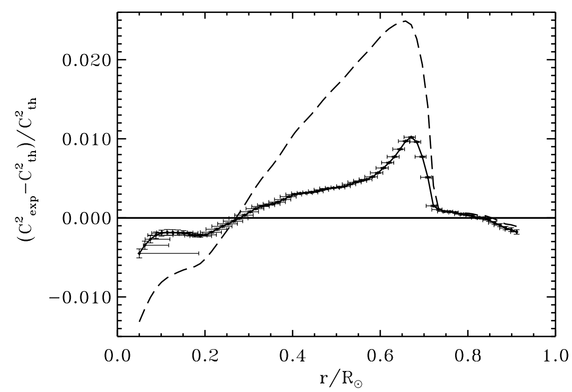

Figure 4. Sound speed square difference between the Sun as measured by helioseismology and calculated from a solar model without (dashed line) and with diffusion (solid line with error bars). From Brun et al. [22].

A recent improvement concerns the input coming from nuclear-fusion cross sections that are most important for solar energy generation; following a workshop in Seattle (February 1997), most of the specialists have agreed on the best values to use in the models, taking into account the most recent experimental developments. This important work [21] has allowed to reduce the discrepancies observed in the outputs of the different codes. In

[2]Helioseismology studies the periodical solar oscillations observed at the surface of the Sun; they are due to acoustic waves which are excited by pressure forces and propagate in the interior of the Sun (see for example [20]).

[3]The introduction of microscopic diffusion has been checked to be fundamental, after the check of the sound speed measurements coming from helioseismology. This can be shown for example in figure 4.

particular recent measurements concerning the reaction $^7Be(p,\gamma)^8B$ make more reliable, though with a large uncertainty, the predictions concerning the ν_B flux.

Figure 5 illustrates the predictions of the neutrino fluxes coming from the different sources.

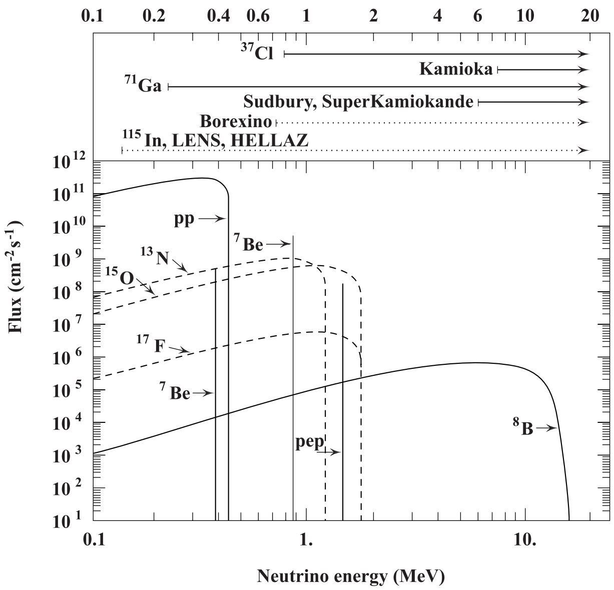

Figure 5. Solar neutrino energy spectrum (adapted from Bahcall [19]). Neutrino fluxes from continuum sources are in $cm^{-2}\,s^{-1}\,MeV^{-1}$. Line fluxes (for pep and Be neutrinos) are in $cm^{-2}\,s^{-1}$. The insert gives the sensitivity interval of the different detectors above the threshold.

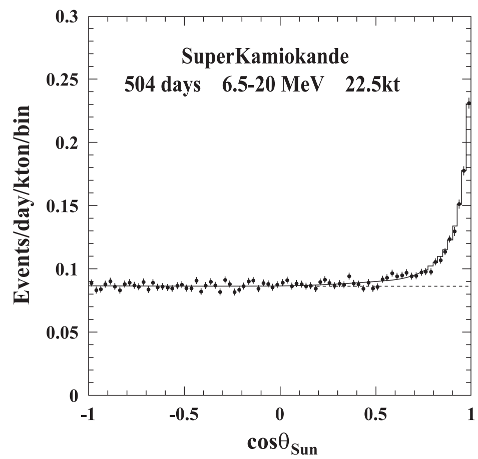

Figure 6. Plot of the cosine of the angle between the electron direction and a radius vector from the Sun in SuperKamiokande. The solid line shows the best fit to the data. From reference [26].

4.1. Solar neutrino experiments

The detection of solar neutrinos started in 1968 with the radiochemical chlorine experiment, settled by R.Davis and his collaborators in the Homestake gold mine (South Dakota, USA). Almost twenty years were necessary to have a second solar neutrino experiment working, the real time Kamiokande experiment, in the Kamioka mine (Japan), replaced since April 1996 by the beautiful SuperKamiokande detector (50 000 tons of water). These two experiments are sensitive only to the most energetic solar neutrinos (mainly ν_B). Radiochemical detectors, using gallium as a target and sensitive to the low energy ν_{pp}, started in 1990-1991, SAGE, in the Baksan Underground Laboratory (Caucasus, Russia) and GALLEX, in the Gran Sasso Underground Laboratory (Italy). One new large experiment, also sensitive only to ν_B , will start in 1999, the Sudbury Neutrino Observatory SNO (Ontario, Canada), which uses heavy water as a target. The Borexino experiment, also in the Gran Sasso and mainly sensitive to ν_{Be}, could start in 2001. All these experiments, with their respective threshold, are represented in figure 5.

Table 1
Predictions of some recent standard solar models for the present detectors. (One SNU is one solar neutrino unit and corresponds to 10^{-36} capture/atom/second.)

Detector	BBP [23]	BTCM [22]	FRANEC [24]
chlorine	$7.7\,^{+1.2}_{-1.0}$ SNU	7.2 ± 1.2 SNU	7.4 ± 2.2 SNU
water (Kamiokande)	$5.15\,^{+0.98}_{-0.72}$ 10^6 cm^{-2} s^{-1}	4.82 ± 1.0 10^6 cm^{-2} s^{-1}	5.16 ± 1.93 10^6 cm^{-2} s^{-1}
gallium	$129\,^{+8}_{-6}$ SNU	127 ± 7 SNU	128 ± 8 SNU

The solar model predictions for the different detectors are obtained by making the convolution of the predictions for the flux with these cross sections. Table 1 quotes the predictions of some recent models. Three main sources, $\nu_{\rm pp}$, $\nu_{\rm Be}$ and $\nu_{\rm B}$ contribute to the predictions. These predictions are relatively close for the gallium, which is sensitive to all sources (about 55 % for $\nu_{\rm pp}$, about 25 % for $\nu_{\rm Be}$ and about 10 % for $\nu_{\rm B}$), but dominated by the robust prediction on $\nu_{\rm pp}$, strongly correlated to the luminosity of the Sun. They are slightly different for the chlorine detector, which is sensitive mainly to $\nu_{\rm Be}$ (about 20 %) and to $\nu_{\rm B}$ (about 75 %) and for (Super)Kamiokande, which is sensitive only to $\nu_{\rm B}$, the uncertainties on these two sources being larger.

4.1.1. The radiochemical chlorine experiment

Davis uses the reaction $\nu_{\rm e}$ + ^{37}Cl $\rightarrow$ ^{37}Ar + e$^-$ (threshold 0.814 MeV) to catch solar $\nu_{\rm e}$. The produced ^{37}Ar isotopes decay by electron capture with a half-life of 35 days. The target consists in 615 tons of perchlorethylene C_2Cl_4 . A run consists in three main steps : the exposure to solar neutrinos (about two months), the argon extraction and the counting of the ^{37}Ar. More than hundred runs have been performed since 1968. The present result [25] is $(2.56 \pm 0.16\,(\text{stat.}) \pm 0.16\,(\text{syst.}))$ SNU, significantly smaller than the predictions of the models (7-8 SNU). The ^{37}Ar production rate is about 0.5 per day and about 750 decays have been counted in the total.

4.1.2. The real time (Super)Kamiokande experiment

The SuperKamiokande target is constituted by a large cylindrical tank containing 10 000 tons of ultra-pure water. The experiment is based on elastic neutrino scattering : $\nu_{\rm e}$ + e$^-$ $\rightarrow$ $\nu_{\rm e}$ + e$^-$. The scattered electron is detected through the Cerenkov light, which is seen by about 11 000 photomultipliers covering 40 % of the inner surface. The distribution in cosθ, where θ is the angle between the trajectory of the electron and the direction of the Sun shows an enhancement near $\cos\theta = 1$ which constitutes the first direct evidence for solar neutrinos (see on figure 6 the preliminary result).

The present result for SuperKamiokande, which already completely supersedes the Kamiokande result, in terms of measured neutrino flux (in units of 10^6 cm^{-2} s^{-1}) is $2.44 \pm 0.05\,(\text{stat.}) \pm 0.08\,(\text{syst.})$ [26] compared to 4.82 ± 1.0 [22] and 5.15 ± 1.0 [23] for solar models. It confirms the deficiency of solar neutrinos first observed in the chlorine experiment. (A model by Dar and Shaviv [27] predicts only 2.5, but has not been checked for the helioseismology constraints). The number of events attributed to solar neutrinos in Kamiokande for the period 1987-1996 was about 800. It is 6800 ± 250 for the first 504 days of SuperKamiokande.

4.1.3. Radiochemical gallium experiments

The main objective of the radiochemical gallium experiments is the detection of the $\nu_{\rm pp}$ which are produced in the primary pp fusion reaction. Indeed the reaction $\nu_{\rm e} + {}^{71}{\rm Ga} \rightarrow {}^{71}{\rm Ge} + {\rm e}^-$ has a threshold of 233 keV only, significantly below the maximum value for $\nu_{\rm pp}$ (420 keV). GALLEX uses as a target a solution of $\rm GaCl_3$ (30 t of Ga) and SAGE directly the gallium metal (55 t of Ga). ^{71}Ge is extracted from the target and its decay observed in small proportional counters.

The final GALLEX result after 65 solar runs (May 1991 - January 1997) is $77 \pm 6\,({\rm stat.}) \pm 5\,({\rm syst.})$ SNU [28], i.e. about 60 % of the predictions of SSM (125-130 SNU). It corresponds to a production rate of 0.7 ^{71}Ge per day, and about 250 ^{71}Ge counts have been observed. The reliability of the detector has been checked with a high intensity (more than 60 PBq) ^{51}Cr neutrino source. Two experiments were performed in 1994 and 1995 where the source was placed in the middle of the detector for about 3 months. The ratio between the activity of the source measured through the ^{71}Ge measurement and the activity directly measured is 0.93 ± 0.08 [29]. This shows that the deficit of solar neutrino flux observed by GALLEX cannot be attributed to experimental artifacts. After the end of the experiment, another check using ^{71}As decay into ^{71}Ge allowed to check at the 1 % level the extraction efficiency of the system and to eliminate some possible hot atom effects [30]. Since spring 1998, GALLEX has been replaced by the GNO (Gallium Neutrino Observatory) experiment which has the objective to monitor the Sun with a larger target mass for a complete solar cycle.

The present SAGE result after 53 solar runs (January 1990 - December 1997) is $66.6 \pm 7\,({\rm stat.}) \pm 4\,({\rm syst.})$ SNU [31], i.e. very similar to the GALLEX value. A calibration has also been performed with a ^{51}Cr neutrino source. The result of the ratio between the activity of the source measured through the ^{71}Ge measurement and the activity directly measured is 0.95 ± 0.13 [32], also validating the solar neutrino result of the SAGE experiment.

4.2. The solar neutrino problem

The longstanding solar neutrino problem consists in the deficits observed by the experiments compared to the predictions of the solar models [4]. Table 2 summarizes the present quantitative estimate.

The values and the statistical significance of the deficits are different for the three types of detectors. This is not a priori surprising, since they are sensitive to different neutrinos, coming from different nuclear reactions, and with different energy spectra. In the past the deficit was mainly attributed to a $\nu_{\rm B}$ deficit, but the predictions concerning $\nu_{\rm B}$ are the less robust : they depend crucially on the central temperature of the Sun ($\rm T_c^{18}$). Many astrophysicists either tried different inputs or introduced new hypotheses in their models

[4] The consequences of these deficits are crucial to pinpoint neutrino oscillations almost independently of solar models, see for example [33].

Table 2
Experimental results of the solar neutrino experiments and comparison to the predictions of the standard solar models of Bahcall, Basu and Pinsonneault (BBP), Brun, Turck-Chièze and Morel (BTCM) and Castellani et al. (FRANEC). Quoted errors are $1\,\sigma$.

Experiment	Experimental results	Experiment/Predictions		
		BBP [23]	BTCM [22]	FRANEC [24]
chlorine [25]	2.56 ± 0.23 SNU	0.33 ± 0.06	0.36 ± 0.07	0.35 ± 0.06
SuperKamiokande [26]	2.44 ± 0.1 10^6 cm^{-2} s^{-1}	0.47 ± 0.09	0.51 ± 0.11	0.47 ± 0.09
GALLEX [28]	77.5 ± 8 SNU	0.60 ± 0.07	0.61 ± 0.07	0.61 ± 0.07
SAGE [31]	66.6 ± 8 SNU	0.52 ± 0.07	0.52 ± 0.07	0.52 ± 0.07
gallium GALLEX + SAGE	72.1 ± 5.7 SNU	0.56 ± 0.06	0.57 ± 0.06	0.56 ± 0.05

to decrease the temperature of the Sun, and, consequently, the $\nu_{\rm B}$ flux. In any case, the observation that the deficit observed is more important for the chlorine experiment than for Kamiokande gives problem, since the chlorine is also sensitive to $\nu_{\rm Be}$ for which the predictions are more robust. This problem has been reinforced by the gallium results, now much more than 5σ from the model predictions, even a so-called minimal nuclear model [22], which predicts 119 SNU.

a) Beryllium neutrinos deficit and astrophysical solutions.

Quantitative calculations which plot the $\nu_{\rm B}$ flux versus the $\nu_{\rm Be}$ flux deduced from the experimental results and from simple solar model independent hypotheses, find a negative value for the $\nu_{\rm Be}$ flux. A typical illustration is given in figure 7, from reference [34], which shows the best fit of the data (which extends largely into the negative region for the $\nu_{\rm Be}$ flux), as well as standard model predictions. A cooler Sun would reduce the nuclear reaction rate and the neutrino flux (but we have to take into account the luminosity constraints); the dotted line illustrates the predictions for such an empirical model, with a power law dependence of the different fluxes as a function of the central temperature of the Sun T_c ($T_c^{-1.2}$ for $\nu_{\rm pp}$, T_c^8 for $\nu_{\rm Be}$ and T_c^{18} for $\nu_{\rm B}$); the best χ^2 is obtained for a reduction of T_c by 5-7 % but the probability is less than 1 %. Many phenomenological analyses [35] argue against an “astrophysical” solution to the $\nu_{\rm Be}$ problem : even those solar models that are able to reduce the $\nu_{\rm Be}$ and $\nu_{\rm B}$ fluxes still cannot come close to reproducing experimentally derived $\nu_{\rm Be}$ and $\nu_{\rm B}$.

The solar neutrino problem looks now quantitatively established. It appears more likely as a $\nu_{\rm Be}$ problem, and we know of no satisfactory nuclear physics or astrophysics solution to the observed deficit.

b) Is neutrino oscillation the solution via the MSW effect ?

The nuclear reactions in the Sun produce only ν_e and the detectors are sensitive only to ν_e (with the exception of Kamiokande which is sensitive to ν_μ and ν_τ, but with a cross

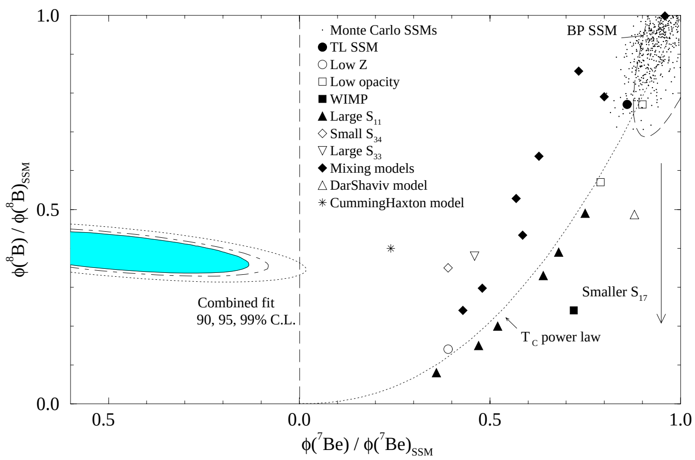

Figure 7. The constraints from the combined experimental data for ν_B flux versus ν_{Be} flux (90 % (grey area) and 95 and 99 % (lines)); the ellipse in the right upper part shows the predictions of the Bahcall and Pinsonneault solar model; small marks represent several non standard solar models and the dotted line characterizes the decrease of the fluxes with the central temperature of the Sun. (From [34]).

section 6-7 times smaller). A transformation of ν_e into ν_μ or ν_τ between the core of the Sun and the detector would clearly induce a decrease of the observed ν_e flux.

The so-called "just so" solution, which considers vacuum neutrino oscillations can be found for example in [34,36]. The experimental results constrain Δm^2 to very small areas at values between 10^{-11} and 10^{-10} eV^2, with a large mixing angle ($\sin^2 2\theta$ above 0.7).

In the case of neutrino oscillations in matter through the MSW effect [18], there is no strong constraint. Because the flavour changing probabilities depend on the neutrino energy and because the various reactions differ sharply in neutrino energies by more than an order of magnitude, the MSW effect has distinguishable effects, depending on the energy weightings, between the different experiments. Taking into account the experimental errors, each experiment defines its own triangular region in the (Δm^2 , $\sin^2 2\theta$) plane . Their overlap defines the allowed areas within a given confidence level (see figure 8a for a recent illustration).

Figure 8b shows the probability of ν_e conversion in the Sun through the MSW effect, superposed to the different solar neutrino fluxes for the small angle solution of the figure 8a. The ν_{pp} flux is not suppressed at all. Most of the ν_{Be} are suppressed as well as the ν_{pep} . The reduction of the ν_B flux is smoothly decreasing from low energy values to higher ones, inducing a modification of the ν_B spectrum. It is clear from this figure that the ν_{Be} can be easily more suppressed than the ν_B, which cannot be done in any standard or non standard solar model.

Though this neutrino oscillation solution is very appealing, we cannot affirm that it is "the" solution. We have to wait for the forthcoming experiments (see next subsection) which should be able, if the small angle solution is the good one, to show either a distortion of the ν_B spectrum (Sudbury and/or SuperKamiokande), or an excess of neutral current events (Sudbury is sensitive to ν_μ and ν_τ interactions via this process), or a disappearance of the ν_{Be} (see for example [37]). SuperKamiokande has shown a preliminary spectrum

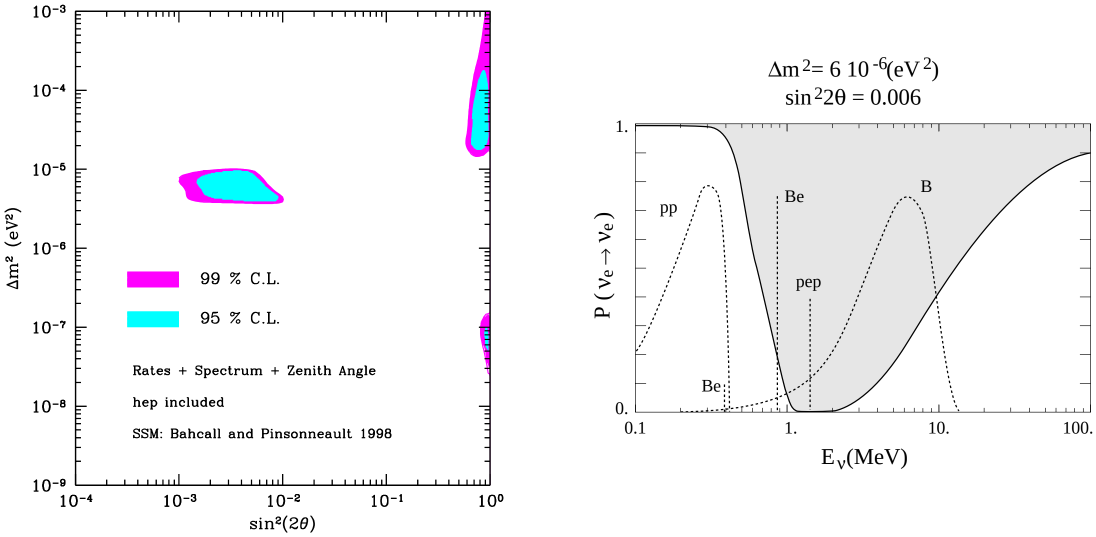

Figure 8. a) Regions of the parameter plane of neutrino oscillation allowed by the MSW effect for interpreting solar neutrino experiments. (From reference [36]). b) Probability of ν_e conversion in the Sun through the MSW effect for the neutrino oscillation parameters which give the best χ^2. The grey area defines the ν_e suppression zone. Dotted lines correspond to the main solar neutrino fluxes (arbitrary vertical scales).

which could show a small distortion [26]. More data are needed but could come soon.

4.3. Future experiments

A new real time experiment (Sudbury Neutrino Observatory, SNO) should start in 1999 in Canada [38]. With a threshold of about 5 MeV, it will be sensitive only to the ν_B. It consists in 1000 tons of heavy water D_2O surrounded by 4 m of purified light water H_2O. The Cerenkov light emitted by the electrons is also detected by photomultipliers. The main difficulty of this experiment is to reduce the backgrounds at a very low level. SNO presents a lot of potential advantages : measurement of the neutrino spectrum, sensitivity to ν_μ and ν_τ via neutral current interactions, sensitivity to a day-night variation of the solar flux, all these effects, through the MSW effect, being able to pinpoint neutrino oscillations independently of solar models.

Borexino [39] is a ultra-high purity real time detector. It consists in a sphere of about 300 tons of liquid organic scintillator viewed by 1700 PM's and shielded by 1 m of organic liquid and 3 m of water. A major difficulty is also to obtain a very pure liquid scintillator. Borexino is mainly sensitive to ν_{Be}. A prototype (called Counting Test Facility) is actually working in the Gran Sasso Underground Laboratory. Borexino could start in 2001.

Among the future projects for the detection of solar neutrinos, we quote : a) HELLAZ [40], based on a high pressure TPC filled with 12 tons of helium, sensitive to ν_{pp} and ν_{Be}, or SuperMUNU, an extension of the MUNU detector (TPC filled with CF_4) presently working at Bugey to search for a magnetic moment of the neutrino, b) bromine [41], also sensitive to ν_{Be}, c) lithium (with a cryogenic detection of the produced ^{7}Be) [42], sensitive to Be and pep neutrinos, d) LENS [43], the most recent idea, using Yb or Gd rare earths and sensitive to pp and Be neutrinos with a reasonable energy resolution.

All these projects still need several years of research and development, or prototype construction. The main objective today would be to have a complete measurement of the solar neutrino spectrum. Before reaching this ambitious objective, the first step is to understand the Be neutrinos (Borexino and a second experiment is needed with good statistics and energy resolution), to check a possible distortion of the ν_B spectrum (SuperK and SNO) and to check the neutral current rate (SNO).

5. REACTOR NEUTRINOS

Nuclear power plants are a powerful source of $\bar{\nu}_e$ of energy of few MeV (Reines and Cowan discovered the "neutrino" close to the Savannah River reactor). There is no reliable detector of $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ at these energies (they interact only via neutral current processes), and all the experiments are disappearance experiments which can test only large mixing angles ($\sin^2 2\theta > 0.1$). Detection is generally based on the process $\bar{\nu}_e + p \to e^+ + n$. The past experiments (Bugey, Gösgen, Krasnoiarsk), all based on a subtraction of events with reactor off from events with reactor on, have not seen any signal of oscillation.

First of a new generation, at distances of ~ 1 km from the reactor, to go down in Δm^2 to values of few $10^{-3}\,eV^2$, the Chooz experiment (Ardennes, France) has presented its first results in the fall 1997. It uses 5 tons of liquid scintillator doped with Gd as a target, surrounded by a 17-ton region for background reduction. It has observed 25 events/day with a background of 1. After having accumulated 1320 ν events, no signal for neutrino oscillations has been observed [44]. The exclusion contour plot is shown on figure 9. A similar experiment is being prepared in Palo Verde (Arizona, USA). The future of reactor experiments could be Perry (Ohio, USA, 15 km from the reactor), or more probably Kamland [45] (at the place of the Kamiokande detector, at a mean distance of 200 km of several reactors), which could be sensitive to values below $10^{-4}\,eV^2$.

6. NEUTRINO OSCILLATION EXPERIMENTS USING ACCELERATORS

6.1. High energy accelerator experiments

Present high energy accelerators (SPS at CERN or Tevatron at Fermilab) provide intense ν_μ beams of mean energy 20-50 GeV. The distance between the neutrino source and the detectors is $\lesssim 1$ km, allowing to explore high Δm^2 values ($\gtrsim 1\,eV^2$). Appearance experiments have been developed in the 90's to search for ν_τ interactions, the ν_τ coming from $\nu_\mu \to \nu_\tau$ oscillations : CHORUS at CERN [47] uses emulsions to identify the short τ range; NOMAD, also at CERN [48] uses a kinematical method based on the missing transverse momentum. Three years of data taking provided about 10^6 ν_μ interactions in which they expect at most few ν_τ . No signal is observed, the limits that they obtain in the (Δm^2 , $\sin^2 2\theta$) plane are drawn in figure 10.

NOMAD and CCFR have also some capabilities to look for ν_e appearance. The background is the ν_e contamination in the ν_μ beam. The exclusion contours are shown on figure 9, excluding the LSND solutions above 10 eV^2.

The future of the CERN experiments could be TOSCA, a mixture of NOMAD and CHORUS.

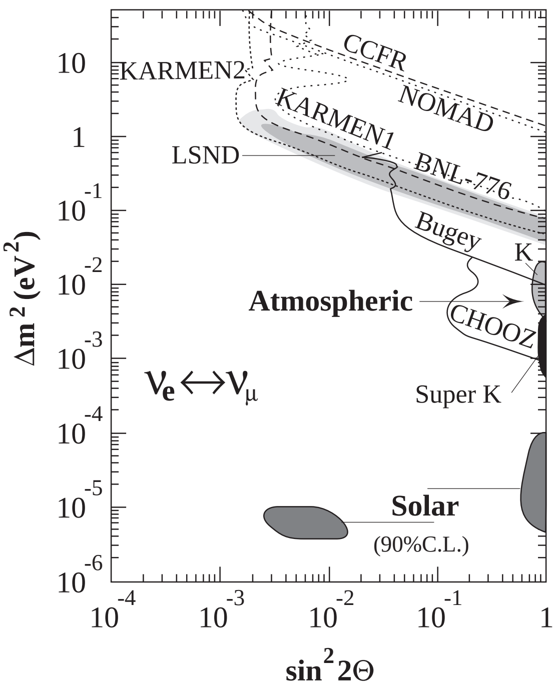

Figure 9. Allowed areas and excluded regions (lines) for $\nu_\mu \leftrightarrow \nu_e$ oscillations. Adapted from [46].

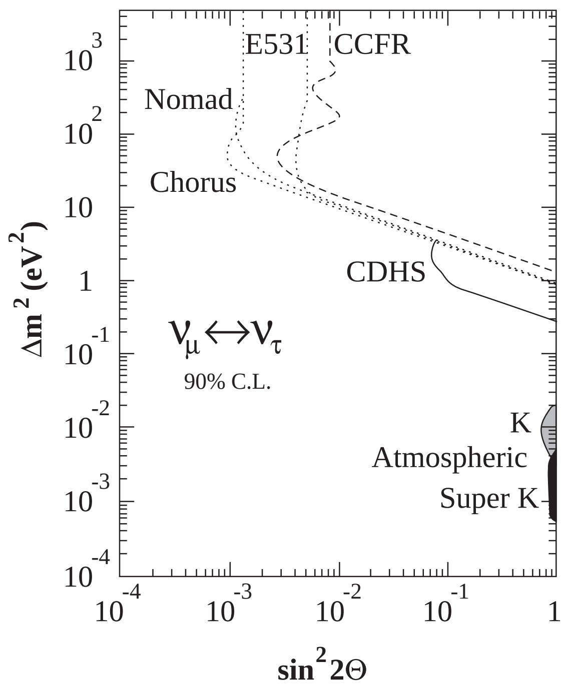

Figure 10. Status of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Adapted from [46].

6.2. The Los Alamos LSND puzzle

A liquid scintillation neutrino detector (LSND) has been designed to detect neutrinos from the 800 MeV proton Los Alamos Meson Physics Facility (LAMPF). The neutrino flux (mixture of ν_μ , ν_e and $\bar{\nu_\mu}$) comes from π^+ and μ^+ decay at rest. The detector, about 30 m from the target, consists in a cylinder 8 m long and 5 m diameter, filled with 167 tons of liquid scintillator, and viewed by 1220 photomultipliers. The authors claim that the present results show evidence for $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillations [53]. The $\bar{\nu_e}$ is detected via the reaction $\bar{\nu_e} + p \to e^+ + n$ correlated with a 2.2 MeV γ coming from $np \to d\gamma$. The signal consists in an excess of 22 events with positron energy between 20 and 60 MeV and only 4.6 ± 0.6 background events (see figure 13) It is interpreted as a $\bar{\nu_e}$ appearance and there is still a small band in the (Δm^2, $\sin^2 2\theta$) plane at $\sin^2 2\theta$ values between 10^{-3} and 10^{-2} and Δm^2 around 1 eV^2 (see figure 9) which is not yet completely excluded by the other experiments, in particular KARMEN [54]. The analysis in the $\nu_\mu \to \nu_e$ channel, using ν_μ from π^+ decays in flight, finds also an excess of events too large to be interpreted by normal ν_e contamination in the beam [55]; its interpretation is consistent with the $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillation evidence.

The reality of the signal has however to be confirmed. There have been some criticisms on the shielding of the detector and on the veto system. The idea to move the detector at a larger distance should also be considered.

The KARMEN detector is a 56 tons segmented liquid scintillator calorimeter installed at 18 m from the beam stop of the spallation neutron facility ISIS at the Rutherford Appleton Laboratory. The beam is very similar to the LAMPF one, but is pulsed, which

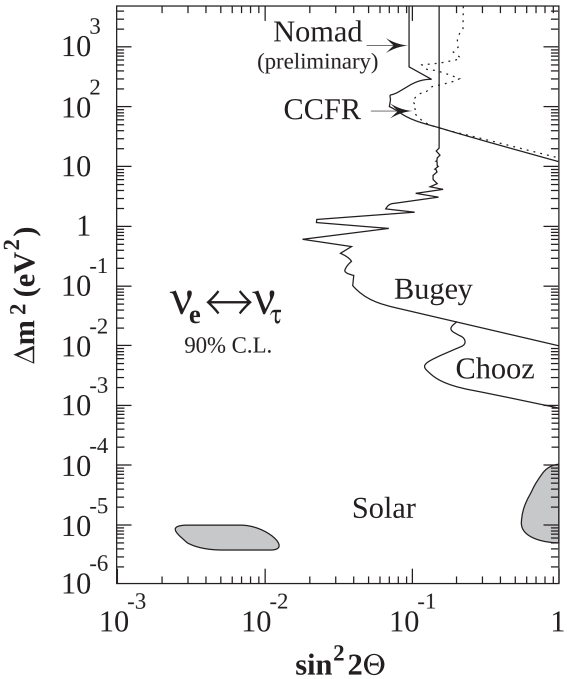

Figure 11. Status of $\nu_e \leftrightarrow \nu_\tau$ oscillations. Adapted from [46].

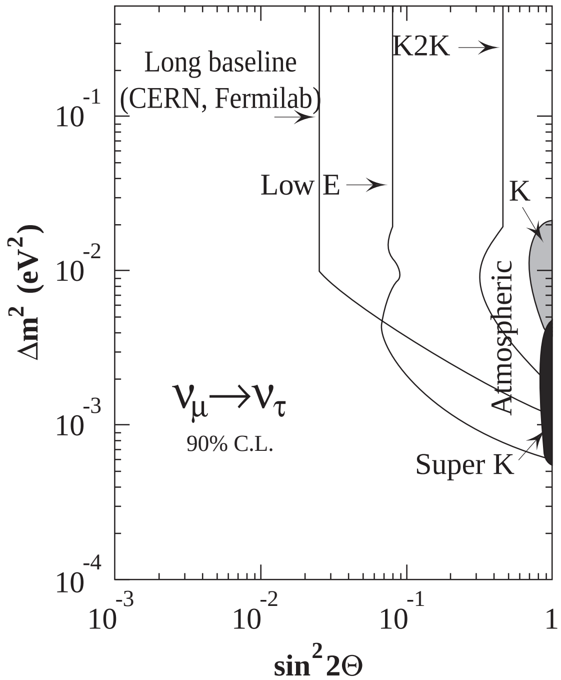

Figure 12. Future experiments looking for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Adapted from [46].

essentially reduces the background to zero. Neutrons are detected through a Gd(n,γ) capture reaction. They have searched for ν oscillations in the disappearance channel $\nu_e \rightarrow \nu_x$, analyzing in particular the spectral shape of electrons from the ν_e induced reaction as well as measuring the absolute ν_e flux. No evidence for neutrino oscillation has been found [54] (see KARMEN1 on figure 9). With KARMEN2, no single candidate event has been detected where a background of few would have been expected. From this lucky situation, they can derive a more severe contour (see KARMEN2 on figure 9) using (preliminary) data which does not leave much place to a signal.

One can see that KARMEN2 and LSND are almost approaching contradiction. More data from KARMEN2 and the MiniBoone experiment planned from 2001 at Fermilab (quoted by J.Conrad in [46]) or I216 at CERN could give the answer.

7. ATMOSPHERIC NEUTRINOS

7.1. Brief historical introduction

Primary cosmic rays interacting in the upper atmosphere produce pions and kaons which decay into muons and neutrinos (see spectrum in figure 1). At first order, in the hadronic cascade, there are as much as positive than negative mesons. We can write :

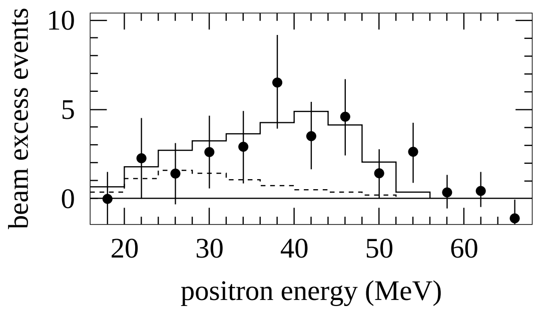

Figure 13. Energy distribution for $\bar{\nu_e}$ events in the LSND experiment. Dashed line represents the expected background. From [53].

$$p + N \rightarrow \pi^+ + \ldots \qquad\qquad + \pi^-$$
$$\hookrightarrow \mu^+ + \nu_\mu \qquad\qquad \hookrightarrow \mu^- + \bar{\nu_\mu}$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu_\mu} \qquad\qquad \hookrightarrow e^- + \bar{\nu_e} + \nu_\mu$$

Simple counting of daughters concludes that :

$$\frac{\nu_\mu + \bar{\nu_\mu}}{\nu_e + \bar{\nu_e}} \approx \frac{2}{1}\,(\pm 5\,\%) \qquad \text{and} \qquad \frac{\nu}{\bar{\nu}} \approx 1 \tag{9}$$

Depending on the interaction point in the atmosphere, the distance traveled by the neutrino varies from 10 km to $1.3\,10^4$ km. The first atmospheric neutrino events were recorded by the first proton decay experiments at the middle of the 80's. There are two types of detectors, Cerenkov like IMB, Kamiokande and now SuperKamiokande and calorimetric like Fréjus or Soudan, and the identification of electrons or muons coming from ν_e or ν_μ interactions is not the same. Low energy events are generally contained in the detector.

The results are presented in the form of the ratio $R\,(\mu/e)$ obtained from data divided by (μ/e) obtained by a Monte-Carlo which takes into account the phenomenological predictions on the flux and angular distribution and the detector characteristics, and a value of 1 is expected. A summary of the main results is found in table 3.

The historical development of the atmospheric neutrino problem is as follows. A significant deficit in the ratio is given by the Kamiokande experiment [49], either in the sub-GeV ($E_{vis} < 1.3$ GeV) or in the multi-GeV ($E_{vis} > 1.3$ GeV) energy range, few hundreds of events in total. But it is difficult to reconcile with the result of the Fréjus [50] for example. A crude analysis could conclude that Cerenkov experiments find a deficit and not calorimeter experiments, suggesting that the deficit could be due to the difficulty to separate ν_e from ν_μ in the Cerenkov detectors. But the Kamioka collaboration has exposed a 1000 ton water Cerenkov detector to different electron and muon beams beam at KEK; they showed that they were able to separate with a sufficient accuracy the two types of particles [51]. Some possible systematic errors have been checked as the idea that neutron induced events could simulate ν_e interactions (and consequently increasing the ν_e flux with respect with the ν_μ one), but Kamiokande showed that the neutron induced

Table 3
Main results for atmospheric neutrinos.

Experiment	Detector type	$(\mu/e)_{data} / (\mu/e)_{MC}$	Exposure kton.y	Years
Fréjus [50]	calorimeter	$1.00 \pm 0.15 \pm 0.08$	2.0	1984-1988
IMB	Cerenkov	$0.54 \pm 0.02 \pm 0.07$	7.7	1982-1991
Kamiokande [49]	Cerenkov	$0.60 \pm 0.06 \pm 0.05$	7.7	1988-1994
(multi-GeV)		$0.57 \pm 0.08 \pm 0.07$	6.0	1988-1994
Soudan2 [57]	calorimeter	$0.64 \pm 0.11 \pm 0.06$	3.9	1993-1998
SuperK [56]	Cerenkov	$0.63 \pm 0.03 \pm 0.05$	33	1996-1998
(multi-GeV)		$0.65 \pm 0.05 \pm 0.08$	33	1996-1998

Table 4
Summary of the up/down ratio for e-like and μ-like events from SuperKamiokande and Kamiokande (similar systematic errors to SuperK). From [56].

	SuperKamiokande		Kamiokande
	Monte Carlo	Data	Data
e-like			
Sub-GeV, <400 MeV/c	$1.00\pm0.04\pm0.03$	$1.20\pm0.11\pm0.03$	$1.29^{+0.27}_{-0.22}$
Sub-GeV, >400 MeV/c	$1.02\pm0.04\pm0.03$	$1.10\pm0.11\pm0.03$	$0.76^{+0.22}_{-0.18}$
Multi-GeV	$1.01\pm0.06\pm0.03$	$0.93\pm0.13\pm0.02$	$1.38^{+0.39}_{-0.30}$
μ-like			
Sub-GeV, <400 MeV/c	$1.05\pm0.03\pm0.02$	$1.03\pm0.11\pm0.02$	$1.18^{+0.31}_{-0.24}$
Sub-GeV, >400 MeV/c	$1.00\pm0.03\pm0.02$	$0.65\pm0.06\pm0.01$	$1.09^{+0.22}_{-0.18}$
Multi-GeV	$0.98\pm0.03\pm0.02$	$0.54\pm0.06\pm0.01$	$0.58^{+0.13}_{-0.11}$

background was negligible [52]. The situation was such few years ago. The measured small values of R suggested already the possibility of neutrino oscillations.

Later on, with more data Kamiokande could show that the value of R in the "multi-GeV" energy region had a dependence on the zenith angle (see table 4). Since there is a large difference in zenith path-length between upward going (about 10 000 km) and downward-going neutrinos (about 20 km), a zenith angle dependence of R can be interpreted as additional evidence for neutrino oscillations.

The interpretation in terms of $\nu_\mu \to \nu_e$ oscillations is essentially ruled out by the Chooz experiment as can be see on fig. 10. The "positive" contour plot for neutrino oscillations interms of ν_μ disappearance such as $\nu_\mu \to \nu_\tau$ oscillations is shown in figure 14 for Kamiokande together with the "negative" (exclusion) contour plot of Fréjus.

7.2. The SuperKamiokande announcement and the present situation

In June 1998, the first atmospheric neutrino measurements from the SuperKamiokande detector have been presented [56]. With an analyzed fiducial volume exposure of 33

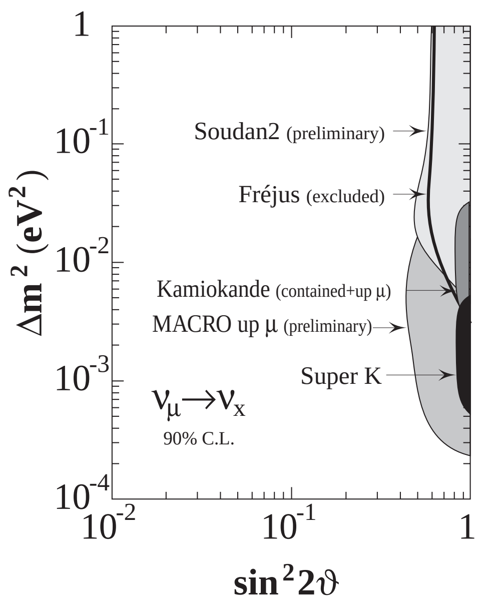

Figure 14. Summary of the situation in the "atmospheric" region.

kiloton-years, R and its zenith angle dependence were measured with much higher statistics than Kamiokande (more than 1000 mu-like and 1000 e-like events in the sub-GeV region and about 1000 events in total in the multi-GeV region). The same effects are seen (low value of R and zenith-angle dependence of R). This is shown in tables 3 and 4 and figure 15. However (table 4, the angular dependence of R is somewhat seen also in the sub-GeV region (400 MeV to 1 GeV) contrary to Kamiokande. This is probably why the "positive" contour for neutrino oscillations of SuperKamiokande has little overlap with Kamiokande (figure 14).

To be complete, one must add that so far the Soudan experiment, a 960-ton tracking calorimeter (224 modules consisting of finely segmented iron instrumented with 1 m long drift tubes), does not observe a zenith angle dependence of R although R is found significantly smaller than unity [57]. Their "positive" contour plot is shown in figure 14.

In conclusion, the zenith angle distribution of R observed first in Kamiokande and later with much more statistics in SuperKamiokande together with the small average value of R are now very significantly different from the predictions in the absence of neutrino oscillations but the agreement in terms of contour plots for neutrino oscillations between Kamiokande, SuperKamiokande, Soudan and Fréjus is rather marginal.

One should note that first, the zenith angle dependence (up/down) might suffer from the huge background of downwards going muons which have to be vetoed, and second, that the atmospheric neutrino detectors poorly measure so far the basic parameters L and E to really see the oscillation pattern in L/E. There is room for better atmospheric detectors like ANTARES [58], Aquarich, ICARUS [59] or a high density calorimeter [60], to explore the L/E pattern corresponding to Δm^2 from 10^{-4} to $10^{-2}\mathrm{eV}^2$, and also for experiments aiming at a better measurement of the produced atmospheric neutrino fluxes.

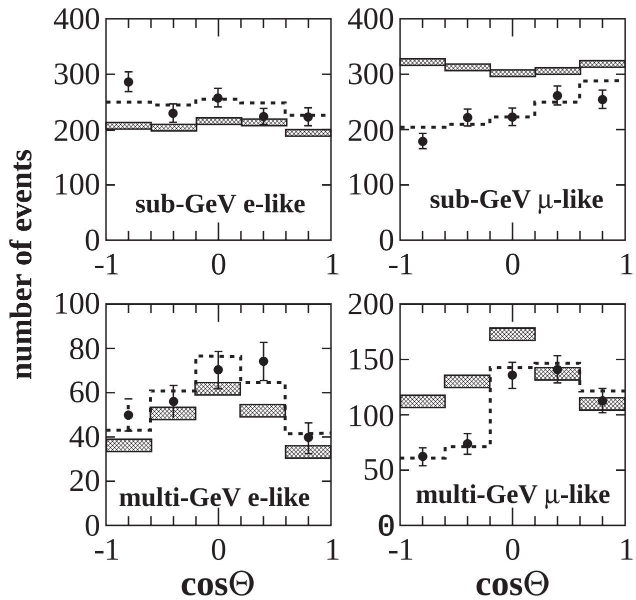

Figure 15. Zenith angle distributions of μ-like and e-like events for sub-GeV and multi-GeV events in SuperKamiokande [56]. Upward (downward) for $\cos\theta > 0$ (< 0). Grey area is Monte-Carlo predictions. Dashed line is predictions for the best fit for neutrino oscillations.

Finally, from the measurement of upward going muons (induced by interactions of atmospheric ν_μ coming from the down hemisphere in the rock around the detector), one can also obtain information on a possible oscillation, but the theoretical uncertainties are still high. From 398 upgoing muons, MACRO measures the flux of ν induced upgoing muons. The ratio of the number of observed to expected events is $0.74 \pm 0.036(\text{stat.}) \pm 0.046(\text{syst.}) \pm 0.13(\text{theor.})$ and the zenith distribution does not fit well with the no oscillation expectation. These results are compatible with neutrino oscillations [61] and the "positive" contour is shown on figure 14. SuperKamiokande [56] has also presented results on upgoing muons, giving a value of $0.52 \pm 0.07 \pm 0.01$, interpreted by neutrino oscillation (see also figure 14).

The interpretation in terms of neutrino oscillations is constrained by the Chooz experiment such that a $\nu_e \rightarrow \nu_\mu$ is ruled out (figure 9). Concerning the $\nu_\mu \rightarrow \nu_\tau$ interpretation the possible range of Δm^2 is from 5 10^{-4} to 10^{-1}eV^2; values above are ruled out by accelerator experiments (CDHS on figure 10).

7.3. Back to accelerators : long baseline experiments

To explore smaller Δm^2 values with accelerator and probe the atmospheric neutrino indications, it is necessary to increase the distance L between the accelerator and the detector, without forgetting that the flux decreases in $1/L^2$, obliging to increase the dimensions of the detector. Several long baseline neutrino beams are being built or still in discussion at KEK (Japan), Fermilab and CERN. Figure 12 presents the expected contours from these future experiments.

The most advanced project is the Japanese one with a beam (<E_ν>~2 GeV) between the KEK accelerator and the Kamioka mine. Three detectors are planned, a 1.7 kton detector at 0.5 km, a larger one at 25 km and SuperKamiokande (50 kton) at 250 km. It will explore the area where Kamiokande and SuperKamiokande have evidence for neutrino oscillations from atmospheric neutrinos.

At Fermilab, the MINOS project (10 kton of magnetized iron in the Soudan mine, 730 km N.O. of Fermilab) could start in 2001 [62]. At CERN, the beam (to be decided) would be directed towards the Gran Sasso (732 km S.E.) where several detectors (ICARUS [59], NOE [63], NICE, OPERA [64], Aquarich, ...) have been proposed.

8. OVERALL PICTURE FOR NEUTRINO OSCILLATIONS

Figures 9, 11 and 10 summarize the experimental situation. As we have seen, the results of LSND could be interpreted as a $\nu_\mu \to \nu_e$ oscillations, while the only interpretation for the low value of R in atmospheric neutrinos and its zenith angle distribution is $\nu_\mu \to \nu_\tau$ oscillations. The natural interpretation for the solar neutrino deficit would then be $\nu_e \to \nu_\tau$ oscillations. Unfortunately, this does not work because, for three neutrino species one expects to have $\Sigma\Delta m^2$ equal to zero, which obviously is not the case with the kind of favoured values for Δm^2 . So one experimental evidence should be wrong, unless one invokes a fourth family which then must be sterile (not coupled to Z^0 in order to have escaped the LEP limit on the number of neutrino families).

9. PERSPECTIVES ON NEUTRINOS

The future of neutrinos is very rich. Many experiments are looking for neutrino masses or explore the Universe using neutrinos. Direct searches for neutrino masses have failed until now, with an upper limit of about 5 eV for the ν_e . Double beta decay experiments explore also the Majorana or Dirac nature of the neutrino and new detectors are being built. They could reach limits as low as 0.1 eV for an effective mass of the ν_e . Neutrino oscillations seem to be a promising avenue to finally pinpoint neutrino masses and physics beyond the standard model of particle physics. Experiments looking for (or interpreted by) neutrino oscillations present three different evidences:

a) the MSW effect as the solution of the solar neutrino problem is very attractive; the forthcoming results from SuperKamiokande (possible spectrum distortion) but especially of SNO (neutral current events and/or spectrum distortion) and Borexino (ν_{Be} deficit) should tell us within few years if it is the truth;

b) the atmospheric neutrino observation shows a strong evidence for a $\nu_\mu \to \nu_\tau$ oscillation from the SuperKamiokande data (the $\nu_e \to \nu_\mu$ interpretation is ruled out by Chooz and by the SuperK data themselves), but to our mind this interpretation needs to be confirmed by better atmospheric neutrino detectors and/or by long baseline experiments;

c) the puzzling phenomenon observed by LSND at Los Alamos is not confirmed so far by KARMEN.

It is very unlikely that the three evidences could simultaneously be true. Which ones will survive is not predictable presently. The forthcoming year(s) will be a fascinating time for neutrino physics.

Acknowledgements

It is a pleasure to thank J.Bouchez, M.Cribier, G.Fiorentini, B.Frois, L.Moscoso and S.Turck-Chièze for enlightning discussions.

REFERENCES

1. Particle Data Group, Eur. Phys. J. C3 (1998) 1.
2. J. Ellis et al., Phys. Lett. B292 (1992) 189.
3. G. Gelmini and E. Roulet, Rep. on Prog. in Physics 58 (1995) 1207.
4. S.Sarkar, Nucl. Phys. B (Proc. Suppl.) 66 (1998) 168.
5. M. Cribier, M. Spiro, D. Vignaud, "La lumière des neutrinos", Editions du Seuil (Paris), 1995.
6. E. W. Kolb, M. S. Turner, The Early Universe, Addison Wesley (1990) ; G. G. Raffelt, Stars as Laboratories for Fundamental Physics, The University of Chicago Press (1996).
7. P. Langacker, J. P. Leveille, J. Sheiman, Phys. Rev. D27 (1983) 1228.
8. I. Ferreras and I. Wasserman, Phys. Rev. D52 (1995) 5459.
9. J. Dias de Deus and M. Pimenta, Proc. of the Moriond Meeting, January 1995, p. 255.
10. C. Weinheimer et al., Phys. Lett. B300 (1993) 210 ; J. Bonn, Proc. of ν'96, Helsinki, World Scientific, ed. K.Enqvist, K.Huiti, J.Maalampi, p. 259.
11. A. I. Belesev et al., Phys. Lett. B350 (1995) 263.
12. H. V. Klapdor-Kleingrothaus, Proc. of ν'96, Helsinki, World Scientific, ed. K.Enqvist, K.Huiti, J.Maalampi, p. 317.
13. P.J.Kernan and L.M.Krauss, Nucl. Phys. B437 (1995) 243.
14. K.Assamagan et al., Phys. Rev. D53 (1996) 6065.
15. ALEPH Collaboration, Eur. Phys. J. C2 (1998) 395.
16. L.Baudis et al., Phys. Lett. B407 (1997) 219.
17. D.Lalanne and C.Sean Sutton, LAL Report 98-52, to be published in Proc. of the WEIN Conf., Santa Fé, June 1998.
18. S. P. Mikheyev and A. Yu. Smirnov, Nuovo Cimento 9C (1986) 17 ; L. Wolfenstein, Phys. Rev. D17 (1978) 2369.
19. J. N. Bahcall, "Neutrino Astrophysics", Cambridge University Press, 1989.
20. S. Turck-Chièze, W. Däppen, E. Fossat, J. Provost, E. Schatzman and D. Vignaud, Phys. Rep. 230 (1993) 57.
21. E.G.Adelberger et al., Rev. Mod. Phys. 70 (1998) 1265.
22. A.S.Brun, S.Turck-Chièze and P.Morel, Ap. J. 506 (1998) 913.
23. J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. 67 (1995) ; J.N.Bahcall, S.Basu and M.H.Pinsonneault, Phys. Lett. B433 (1998) 1.
24. V.Castellani, S.Degl'Innocenti, G.Fiorentini, M.Lissia and B.Ricci, Physics Reports 281 (1997) 309.
25. B.T.Cleveland et al., Ap. J. 496 (1998) 505.
26. Y.Fukuda et al., Phys. Rev. Lett. 81 (1998) 1158 ; Y.Suzuki, talk at Neutrino'98, Takayama, Japan.
27. A. Dar and G. Shaviv, Ap. J. 468 (1996) 933.
28. GALLEX Collaboration, W. Hampel et al., Phys. Lett. B388 (1996) 384 ; W.Hampel et al., to be published in Physics Letters (1999).
29. GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B342 (1995) 440 ; GALLEX Collaboration, W. Hampel et al., Phys. Lett. B420 (1998) 114.
30. GALLEX Collaboration, W.Hampel et al., Phys. Lett. B436 (1998) 158.

31. J. N. Abdurashitov et al., Phys. Lett. B328 (1994) 234 ; V.N.Gavrin, talk at Neutrino'98, Takayama, Japan.
32. J.N.Abdurashitov et al., Phys. Rev. Lett. 77 (1996) 4708.
33. M.Spiro and D.Vignaud, Phys. Lett. B242 (1990) 279.
34. N.Hata and P.Langacker, Phys. Rev. D56 (1997) 6107
35. See for example N. Hata, S. Bludman and P. G. Langacker, Phys. Rev. D49 (1994) 3622 ; J. N. Bahcall and H. A. Bethe, Phys. Rev. D47 (1993) 1298 ; V. Berezinsky, G. Fiorentini and M. Lissia, Phys. Lett. B365 (1996) 185.
36. J. N. Bahcall, P. I. Krastev and A. Yu. Smirnov, Phys. Rev. D58 (1998) 096016
37. G. Fiorentini, M. Lissia, G. Mezzorani, M. Moretti and D. Vignaud, Phys. Rev. D49 (1994) 6298 ; J.N.Bahcall, P.I.Krastev and E.Lisi, Phys. Rev. C55 (1997) 494.
38. G.Jonkmans, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 329 ; R.G.H.Robertson, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 332.
39. S.Malvezzi et al., Nucl. Phys. B (Proc. Suppl.) 66 (1998) 346 ; G.Alimonti et al., Astroparticle Phys. 8 (1998) 141.
40. A. de Bellefon, Nucl. Phys. B (Proc. Suppl.) 70 (1999) 386.
41. A. Alessandrello et al., Astroparticle Phys. 3 (1995) 239
42. M.Galeazzi et al., Phys. Lett. B398 (1997) 187.
43. R.S.Raghavan, Phys. Rev. Lett. 78 (1997) 3618.
44. M. Apollonio et al., Phys. Lett. B420 (1998) 397.
45. See http://www.awa.tohoku.ac.jp/html/KamLAND/index.html
46. J.Conrad, plenary talk at ICHEP, Vancouver, July 1998, hep-ex/9811009.
47. E.Eskut et al., Phys. Lett. B434 (1998) 205 and Phys. Lett. B435 (1998) 458.
48. J.Altegoer et al, Phys. Lett. B431 (1998) 219.
49. Y. Fukuda et al., Phys. Lett. B335 (1994) 237.
50. Ch. Berger et al., Phys. Lett. B245 (1990) 305.
51. S.Kasuga et al., Phys. Lett. B374 (1996) 238.
52. Y. Fukuda et al., Phys. Lett. B388 (1996) 397.
53. C. Athanassopoulos et al., Phys. Rev. Lett. 77 (1996) 3082.
54. B. Armbruster et al., Phys. Rev. C57 (1998) 3414.
55. C. Athanassopoulos et al., Phys. Rev. C58 (1998) 2489.
56. Y.Fukuda et al., Phys. Rev. Lett. 81 (1998) 1562 ; Phys. Lett. B436 (1998) 33.
57. W.W.M.Allison et al., Phys. Lett. B391 (1997) 491 ; W.W.M.Allison et al., preprint hep-ex/9901024.
58. L.Moscoso, talk at Neutrino'98, Takayama (Japan), preprint hep-ex/9809020.
59. A.Rubbia, Nucl. Phys. B (Proc. Suppl.) 66 (1998) 436.
60. M.Aglietta et al., "Measurement of Atmospheric Neutrino Oscillations with a High-Density Detector", CERN/SPSC 98-28, October 1998.
61. M.Ambrosio et al., Phys. Lett. B434 (1998) 451.
62. See http://www.hep.anl.gov/NDK/Hypertext/numi.html
63. See http://www1.na.infn.it/wsubnucl/accel/noe/noe.html
64. See http://www1.na.infn.it/wsubnucl/accel/neutrino/opera.html