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NEUTRINO PHYSICS AND ASTROPHYSICS

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ABSTRACT

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 the neutrino mass, mainly via the search for neutrino oscillations or for double beta decay processes, and on several facets of neutrino astronomy : cosmological neutrinos, neutrinos as witnesses of the life of stars (solar neutrinos), neutrinos as messengers of the death of stars (supernovæ neutrinos).

1. Introduction

Invented by Pauli in 1930, named by Fermi in 1933 and discovered by Reines 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 $n_\nu = 2.991 \pm 0.016$ 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 (the right-handed neutrino is omitted from the fermion spectrum). However, all the other fermions (i.e. quarks and other leptons) are massive and, beyond the existing physics arguments, a simple æsthetical principle says that there is no reason why it should be different for neutrinos. In this respect, massive neutrinos are a crucial test to go beyond the “boring” minimal standard model (in spite of its successes 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 :

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

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 :

$m(\nu_e)/m(\nu_\mu)/m(\nu_\tau) \approx 10^{-6}/10^{-3}/1$. 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.

Section 2 will review the neutrino properties, focussing particularly on its 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 subsections describe experiments close to accelerators and reactors. Several facets of neutrino astronomy (cosmological neutrinos, solar neutrinos, neutrinos from supernovæ, atmospheric neutrinos) will be presented in section 3, some of them strongly connected to ν oscillations. Two puzzling experiments, LSND and KARMEN will be briefly discussed in section 4. The outlook in section 5 will summarize the perspectives.

2. Neutrino properties (is ν massive?)

The neutrino mass is not known and there is an important property of the neutrino which is still puzzling : is the neutrino a Dirac or a Majorana particle? (We do not consider in this review 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 experiments can test this mechanism authorized by quantum mechanics).

2.1. 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 use tritium decay (${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$). 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 than 1 eV is needed. Two experiments, one in Mainz (Germany) ⁵, and the other in Troitsk (Russia) ⁶

recently improved previous limits ($m(\nu_e) < 5.6 \text{ eV}$ for Mainz and 3.5 eV for Troitsk) (see figure 1 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 $-27 \pm 20 \text{ eV}^2$. 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 1: Energy spectrum of the Mainz tritium β -decay experiment close to the endpoint ⁵. The line is the fit to the data. The insert shows the expected fit for different ν masses.

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 :

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

Though values as low as 10 eV have been quoted, it is considered that the realistic limit is $m(\nu_e) \lesssim 20 \text{ eV}$ (see for example ⁷).

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 $m(\nu_\mu) < 170 \text{ keV}$ ⁸, 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 $m(\nu_\tau) < 23 \text{ MeV}$ ⁹.

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 :

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

This value slightly depends on the Hubble constant, and more details can be found in reference ¹⁰. In reality, the situation is slightly more complicated : cosmological

constraints apply in the plane ν lifetime versus ν mass ¹⁰.

2.2. Double beta decay experiments

Double beta decay of a nucleus X can be written :

$${}^A_Z X_N \rightarrow {}^A_{Z+2} X_{N-2} + 2e^- (+ 2\bar{\nu}_e) \quad (4)$$

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 (${}^{48}\text{Ca}$, ${}^{76}\text{Ge}$, ${}^{82}\text{Se}$, ${}^{100}\text{Mo}$,...), 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 $T_{1/2}^{0\nu}$:

$$\langle m_\nu \rangle^2 = G^{0\nu} |M^{0\nu}|^2 / T_{1/2}^{0\nu} \quad (5)$$

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 ${}^{76}\text{Ge}$ in the underground Gran Sasso laboratory. The present result is $T_{1/2}^{0\nu} > 9.6 \cdot 10^{24} \text{ y}$ ¹¹ (see figure 2), inducing a limit of 0.5 eV (90 % c.l.) on $\langle m_\nu \rangle$. Several years of running should give a limit of 0.1 eV. The NEMO 3 detector (10 kg of foils of ${}^{100}\text{Mo}$) 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 ${}^{136}\text{Xe}$ 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 ¹¹.

2.3. 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 subsections.

Figure 2: Energy spectrum observed by the Heidelberg-Moscow experiment after 17.17 kg.y measuring time ¹¹.

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 :

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

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 :

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \times \sin^2(\pi l/l_v) \quad (7)$$

$l_v = 4\pi E/\Delta m^2$ 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 , $l_v(\text{m}) = 2.5 E/\Delta m^2$.

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 $(\Delta m^2, \sin^2 2\theta)$ 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 $\gtrsim 1 \text{ eV}^2$ for present experiments where l is about 1 km, smaller values for long baseline experiments which are planned at distances of about 1000 km); neutrinos from reactors (short distances but small energies) and atmospheric neutrinos explore between 10^{-2} 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 ⁴⁷, could explain the observed deficit of solar neutrinos as will be seen later.

2.4. Neutrino oscillation experiments using accelerators

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 ($\gtrsim 1 \text{ eV}^2$). New appearance experiments have been developed these last years to search for ν_τ interactions, the ν_τ coming from $\nu_\mu \rightarrow \nu_\tau$ oscillations : CHORUS at CERN ¹² uses emulsions to identify the short τ range ; NOMAD, also at CERN ¹³ uses a kinematical method based on the missing transverse momentum. They are presently taking data and should provide their first results in the summer 1997. Three years of data taking should provide about 10^6 ν_μ interactions in which they expect at most few ν_τ . If no signal is observed, the limits that they should obtain in the $(\Delta m^2, \sin^2 2\theta)$ plane are drawn in figure 3.

The future of the CERN experiments is still in discussion and a mixture of CHORUS and NOMAD could be proposed ¹⁴. The COSMOS experiment at Fermilab, using also emulsions, could start in 2001 and register 10×10^6 neutrino events in 4 years, with an expected ν_τ -like background events less than 2. The purpose of these experiments would be to go to smaller values of the mixing angle.

To explore smaller Δm^2 values, 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. Serious proposals for long baseline neutrino beams are being discussed at Fermilab, CERN and KEK (Japan).

The most advanced project is the Japanese one where the beam ($\langle E_\nu \rangle \sim 2 \text{ GeV}$) between the KEK accelerator and the Kamioka mine could be ready in 1998. 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 has some evidence for neutrino oscillations from atmospheric neutrinos (see subsection 3.4).

At Fermilab, the MINOS project (10 kton of magnetized iron in the Soudan mine, 730 km N.O. of Fermilab) could be funded soon and start in 2001. At CERN, the beam (to be decided) would be directed towards the Gran Sasso (732 km S.E.) where a liquid argon detector like ICARUS (several modules of 600 tons) could be built. A first test could be made earlier in the Jura mountain using the present beam and a

Figure 3: Oscillation parameters plane. Unless indicated "allowed", the areas on the right of the curves are excluded; full lines for existing results, dotted lines for experiments in progress or planned experiments.

prototype of ICARUS (17 km E.)¹⁵.

2.5. Neutrino oscillation experiments using reactors

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 $\bar{\nu}_e + p \rightarrow e^+ + n$. The past experiments (Bugey, Gösgen, Krasnoyarsk, for the most recent ones), all based on a subtraction of events with reactor off from events with reactor on, have not seen any signal of oscillation (see figure 3).

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) just started to take data at the end of 1996 and could present his first results in the summer 1997. It uses 5 tons of liquid scintillator doped with Gd and should observe about 30 events/day with a background of 2.5. A similar experiment is being prepared in Palo Verde (Arizona, USA). The future of this technique could be Perry (Ohio, USA, 15 km from the reactor), which could be sensitive to values as low as few 10^{-4} eV^2 .

3. Neutrino astronomy

Neutrino astronomy extends from few meV for cosmological neutrinos (with fluxes as large as $10^{20} \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$) to probably 10^{20} eV for neutrinos coming from AGN (with fluxes smaller than $10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$). Figure 4 illustrates the spectrum of the different sources.

3.1. 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 ^{4,10}). 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 $m_\nu=10 \text{ eV}$).

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. ¹⁷) is that their wavelength (few mm) is large compared to the in-

Figure 4: Energy spectrum of the different astronomical (or terrestrial) sources of neutrinos (from ¹⁶).

teratomic 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 $O(G_F)$) ¹⁸, 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 ¹⁹). Their detection is still a real challenge.

3.2. 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 : $p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ 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 ${}^4\text{He}$ nucleus :

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 ²⁰, 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) ^a.

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, ... But the different authors (BP for Bahcall and Pinsonneault ²², TCL for Turck-Chièze and Lopes ²³ and DS for Dar and Shaviv ²⁴ for some recent models) do not always agree on these ingredients, and publish different results. Among the recent improvements, we should quote the introduction of element diffusion processes and different approaches on screening. A part of the differences between the numerical values comes from the nuclear cross sections used, particularly for the reaction $p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$ which has large uncertainties and directly determines the ν_{B} flux. Figure 5 illustrates the predictions for the neutrino fluxes coming from the different sources.

3.2.1. 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). These two experiments are sensitive only to the most energetic solar neutrinos (mainly ν_{B}). New radiochemical detectors, using gallium as a target and sensitive to the low energy ν_{pp} , are taking data since 1990-1991. One, SAGE, is in the Baksan Underground Laboratory (Caucasus, Russia) and the other, GALLEX, in the Gran Sasso Underground Laboratory (Italy). SuperKamiokande (Japan) started in 1996 ^b and another large experiment, also sensitive only to ν_{B} , will start at the end of 1997, the Sudbury Neutrino Observatory SNO (Ontario, Canada), which uses heavy

^aHelioseismology 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 ²¹).

^bSuperKamiokande ²⁸ is a significant extension of Kamiokande : 50000 tons of pure water with 11 000 photomultipliers.

Figure 5: Solar neutrino energy spectrum (adapted from Bahcall ²⁰). Neutrino fluxes from continuum sources are in $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$. Line fluxes (for pep and Be neutrinos) are in $\text{cm}^{-2} \text{s}^{-1}$. The insert gives the sensitivity interval of the different detectors above the threshold. Full lines: existing detectors. Dashed lines: detectors under construction. Dotted lines: projects.

water to trap solar ν_e . The Borexino experiment, also in the Gran Sasso and mainly sensitive to ν_{Be} , could be funded soon. All these experiments, with their respective threshold, are represented in figure 5.

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. Most of the other recently published models (see for example ²⁵) give predictions in the same range.

Three main sources, ν_{pp} , ν_{Be} and ν_{B} contribute to the predictions. These predictions are relatively close for the gallium, which is sensitive to all sources (about 55 % for ν_{pp} , about 25 % for ν_{Be} and about 10 % for ν_{B}), but dominated by the robust prediction on ν_{pp} , strongly correlated to the luminosity of the Sun. They are more different for the chlorine detector, which is sensitive mainly to ν_{Be} (about 20 %) and to ν_{B} (about 75 %) and for (Super)Kamiokande, which is sensitive only to ν_{B} , the uncertainties on these two sources being much larger.

a) The radiochemical chlorine experiment.

Davis uses the reaction $\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$ (threshold 0.814 MeV) to catch

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	BP ²²	TCL ²³	DS ²⁴
chlorine	$9.3^{+1.2}_{-1.4}$ SNU	6.4 ± 1.4 SNU	4.1 ± 1.2 SNU
water (Kamiokande)	$6.6^{+0.9}_{-1.1}$ $10^6 \text{ cm}^{-2} \text{ s}^{-1}$	4.4 ± 1.1 $10^6 \text{ cm}^{-2} \text{ s}^{-1}$	2.5 $10^6 \text{ cm}^{-2} \text{ s}^{-1}$
gallium	137^{+8}_{-7} SNU	123 ± 7 SNU	115 ± 6 SNU

solar ν_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, and since the beginning, the experiment observes less neutrinos than expected. The present result ²⁶ is $(2.54 \pm 0.14(\text{stat.}) \pm 0.14(\text{syst.}))$ SNU, significantly smaller than the predictions of the models which extend from 4.1 to 9.3 SNU. The ^{37}Ar production rate is about 0.5 per day and about 400 decays have been counted in the total.

b) The real time Kamiokande experiment ²⁷.

The Kamiokande experiment is based on elastic neutrino scattering : $\nu_e + e^- \rightarrow \nu_e + e^-$. The scattered electron is detected through the Cerenkov light emitted and its direction is strongly correlated with the direction of the incoming neutrino. The target is constituted by a large cylindrical tank (16 m high and 15.6 m diameter) containing 2140 tons of ultra-pure water. The Cerenkov light is seen by about 1000 photomultipliers.

The present result in terms of measured neutrino flux (in units of $10^6 \text{ cm}^{-2} \text{ s}^{-1}$) is $2.80 \pm 0.19(\text{stat.}) \pm 0.33(\text{syst.})$ ²⁷ compared to 4.4 ± 1.1 ²³ and 6.6 ± 1.0 ²² for the predictions. It confirms the deficiency of solar neutrinos first observed in the chlorine experiment. The recent DS model ²⁴, which predicts only 2.5, is however compatible with no deficit. The number of events attributed to solar neutrinos for the period 1987-1995 (2079 days) is about 600.

This result has been very recently confirmed by the first announcement of Super-Kamiokande, with a preliminary value $2.51 \pm 0.14(\text{stat.}) \pm 0.18(\text{syst.})$ obtained in about three months only ²⁸.

c) Radiochemical gallium experiments.

The main objective of the radiochemical gallium experiments is the detection of the ν_{pp} which are produced in the primary pp fusion reaction. Indeed the reaction $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$ has a threshold of 233 keV only, significantly below the maximum value for ν_{pp} (420 keV). ^{71}Ge decays ($T_{1/2}=11.43$ days) by electron capture.

Two experiments are now underway, GALLEX and SAGE. The principle is the

same : expose the gallium to solar neutrinos in a low background environment, extract by a chemical method the ^{71}Ge atoms which are produced, transform into counting gas GeH_4 , fill a proportional counter and count them. The main difference is that GALLEX uses as a target a solution of GaCl_3 (30 t of Ga) and SAGE directly the gallium metal (55 t of Ga).

The present GALLEX result after 54 solar runs (May 1991 - October 1995) is $69.7 \pm 6.7 (\text{stat.}) \pm_{-4.5}^{+3.9} (\text{syst.})$ SNU ²⁹, i.e. about 55 % of the predictions of SSM which range from 115 to 137 SNU. It corresponds to a production rate of 0.7 ^{71}Ge per day, and about 220 ^{71}Ge counts have been observed. It constitutes the first evidence for the detection of the primary pp neutrinos produced in the pp fusion reaction in the core of the Sun.

To check the reliability of the detector, two high intensity ^{51}Cr neutrino sources (62.5 PBq) have been built ³⁰. They have been obtained by irradiating 36 kg of chromium enriched in ^{50}Cr (38 % instead of 4.5 % for natural chromium) with the neutrons of the Siloé reactor in Grenoble. They were then placed in the middle of the detector for 3.5 months. The ratio between the activity of the sources measured through the ^{71}Ge measurement and the activity directly measured is 0.91 ± 0.08 ²⁹ (mean value of the two sources). This shows that the deficit of solar neutrino flux observed by GALLEX cannot be attributed to experimental artifacts.

GALLEX stops in 1997, but its natural child, GNO (Gallium Neutrino Observatory) will take the relay at Gran Sasso, with possibly 100 tons of gallium.

The present result of the SAGE experiment after 34 solar runs (1990 - 1995) is $74 \pm 10 (\text{stat.}) \pm 6 (\text{syst.})$ SNU ³¹, i.e. very similar to the GALLEX value.

A calibration has also been performed, using 500 g of highly enriched chromium (86 % of ^{50}Cr). 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.

d) Future experiments.

Two large real time experiments are now underway (SuperKamiokande since April 1996 and Sudbury from summer 1997). With a threshold of about 5 MeV, they are sensitive only to the ν_B . Their main characteristics are displayed in table 2.

The Sudbury experiment ³³ 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 detector which is now in the installation phase in a deep mine near Sudbury in Canada. The main difficulty of this experiment is to reduce the backgrounds at a very low level. This needs in particular the use of low activity materials : less than 10^{-15} g/g of U and Th. The result is obtained by subtracting the H_2O signal to the D_2O signal, the internal target being filled alternatively with the two liquids. The experiment is sensitive to neutral current processes inducing deuterium dissociation by measuring the emitted neutron either a) by capture on ^{35}Cl (after having added for some run some MgCl_2 in the D_2O), or b) using ^3He

^c ^{51}Cr decays by electron capture and emits 750 keV neutrinos.

Table 2: Forthcoming solar neutrino detectors. (SuperKamiokande already started in April 1996).

experiment	reaction	detection threshold	signature	events/yr
SuperKamiokande 50000 tons water Cerenkov 28	$\nu_e e^- \rightarrow \nu_e e^-$	5 MeV	$e > 5$ MeV Sun direction	8000
Sudbury 1000 tons D ₂ O Cerenkov 33	$\nu_e D \rightarrow e^- p p$	6.5 MeV	$e > 5$ MeV (D ₂ O) - (H ₂ O)	6000
	$\nu_x D \rightarrow \nu_x p n$	2.2 MeV	n capture on ³⁵ Cl (D ₂ O + MgCl ₂) - (H ₂ O)	2000
	$\nu_e e^- \rightarrow \nu_e e^-$	5 MeV	$e > 5$ MeV Sun direction	800
Borexino 300 tons liquid scintillator 34	$\nu_e e^- \rightarrow \nu_e e^-$	0.5 MeV	no Sun direction	3000

counters. This experiment presents a lot of potential advantages : measurement of the neutrino spectrum, sensitivity to all neutrino flavours, 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 ³⁴ (see also table 2) 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 presently working in the Gran Sasso Underground Laboratory. Borexino could start in 1998.

About the future projects for the detection of solar neutrinos, we could quote : a) indium ³⁶, sensitive to ν_{pp} , for which the natural radioactivity (10^6 times the expected solar neutrino signal) is a fantastic challenge for physicists but the success would be a real breakthrough, b) HELLAZ ³⁷, based on a high pressure TPC filled with 12 tons of helium, sensitive to ν_{pp} and ν_{Be} , c) bromine ³⁸, sensitive to ν_{Be} , d) lithium iodide, but all these projects still need several years of research and development, or prototype construction. More details on this far future can be found for example in ³⁹.

3.2.2. The solar neutrino problem

The longstanding solar neutrino problem consists of the deficit observed by the experiments compared to the predictions of the solar models. Table 3 summarizes the status of the solar neutrino problem (for recent reviews, see also ⁴⁰). The ratios between the experimental results and the predictions of the BP, TCL and DS models

Table 3: Experimental results of the solar neutrino experiments and comparison to the predictions of the standard solar models of Bahcall and Pinsonneault (BP), Turck-Chièze and Lopes (TCL) and Dar and Shaviv (DS). Quoted errors are 1σ .

Experiment	Experimental results	Experiment/Predictions		
		BP ²²	TCL ²³	DS ²⁴
chlorine ₂₆	2.54 ± 0.20 SNU	0.27 ± 0.05	0.40 ± 0.10	0.62 ± 0.19
Kamiokande ₂₇	2.8 ± 0.4 $10^6 \text{ cm}^{-2} \text{ s}^{-1}$	0.42 ± 0.09	0.64 ± 0.18	1.12 ± 0.48
GALLEX ₂₉	70 ± 10 SNU	0.51 ± 0.08	0.57 ± 0.09	0.61 ± 0.09
SAGE ₃₁	74 ± 12 SNU	0.54 ± 0.09	0.60 ± 0.10	0.64 ± 0.11

(see table 1) show a quantitative estimate of the solar neutrino deficit ^d

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. Until recent years the deficit was mainly attributed to a ν_B deficit. The predictions concerning ν_B are the less robust : they depend crucially on the central temperature of the Sun (T_c^{18}). Many astrophysicists either tried different inputs or introduced new hypotheses in their models to decrease the temperature of the Sun, and, consequently, the ν_B flux. It was not so easy, but part of the community thinks today that some of the different ingredients as the $(p+^7\text{Be})$ cross section are not fully reliable and the corresponding uncertainties may have been underestimated, and that the Kamiokande result alone does not constitute a real problem (as seen for example in table 3 for the DS model).

Even if we accept that there is no deficit for the ν_B , 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 ν_{Be} for which the predictions are more robust. This problem has been reinforced by the gallium results.

a) Beryllium neutrinos deficit and astrophysical solutions.

We first try to interpret the gallium results in a simple consistent model (see figure 6a). The horizontal lines show the gallium results (full line for the value, dotted line for the 1σ error and bold line for the 2σ error). The two first columns illustrate the predictions of two solar models ^{22,23} for the 6 main different sources of neutrinos, grouped here in four main categories (pp+pep, Be, B, CNO cycle). We build a consistent model (third column) assuming that : a) the pp fusion reaction is the dominant energy source of the Sun which means that the $(\nu_{pp} + \nu_{pep})$ flux is given by the solar luminosity ; b) the ν_B flux is given by the Kamiokande observation.

^d The consequences of these deficits are crucial (a value below 78-80 SNU would show evidence for neutrino oscillations almost independently of solar models, see for example ⁴¹).

Figure 6: a) Gallium results (in SNU) and solar model predictions by BP ²² and TCL ²³. The gallium results (full line) correspond to the mean value of GALLEX and SAGE; the dotted (bold) lines define the one (two) σ area. b) Combined fit for ν_B flux versus ν_{Be} flux (90 % (grey area) and 95 and 99 % (dashed lines)) and predictions of standard solar models by Bahcall and Pinsonneault (1992) (BP) and by Turck-Chièze and Lopes (TCL); small circles represent several non standard solar models and the dotted line characterizes the decrease of the fluxes with the central temperature of the Sun. (From ⁴³).

It is clearly seen that the space available for the ν_{Be} flux is very limited. The solar neutrino problem is now essentially a ν_{Be} problem.

Quantitative calculations (see for example ^{42,43,44}) which plot the ν_B flux versus the ν_{Be} flux deduced from the experimental results and from simple solar model independent hypotheses, find a negative value for the ν_{Be} flux. A typical illustration is given in figure 6b, adapted from reference ⁴³, which shows the best fit of the data (which extends largely into the negative region for the ν_{Be} flux), as well as standard model predictions ^{22,23}. 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 ν_{pp} , T_c^8 for ν_{Be} and T_c^{18} for ν_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 ⁴⁵ argue against an "astrophysical" solution to the ν_{Be} problem : even those solar models that are able to reduce the ν_{Be} and ν_B fluxes still cannot come close to reproducing experimentally derived ν_{Be} and ν_B .

We remark here that the models builders, when trying to solve the solar neutrino problem have also to take into account the severe helioseismology constraints through the sound speed deduced from acoustic modes.

The solar neutrino problem looks now quantitatively established. It appears more

likely as a ν_{B_e} 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 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 case of vacuum neutrino oscillations has been studied recently by Krastev and Petcov ⁴⁶. The experimental results constrain Δm^2 to very small areas at values between 10^{-11} and 10^{-10} eV², with a large mixing angle ($\sin^2 2\theta$ above 0.7).

In the case of neutrino oscillations in matter through the MSW effect ⁴⁷, 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 $(\Delta m^2, \sin^2 2\theta)$ plane. Their overlap defines the allowed areas within a given confidence level (see figure 7a).

For non standard models (see for example ⁴²), the small angle solution (which has a very good χ^2 independently of the solar model used) moves towards smaller mixings if the ν_B flux is smaller (or if the central temperature is smaller) and towards larger mixings in the opposite case (see figure 7a where the TCL model predicts less ν_B than the BP model).

Figure 7b 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. The ν_{pp} flux is not suppressed at all. Most of the ν_{B_e} 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_{B_e} 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 Sudbury, SuperKamiokande and Borexino experiments, 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 processes (Sudbury is sensitive to ν_μ and ν_τ interactions via this process), or a disappearance of the ν_{B_e} (see for example ⁴⁸).

3.3. Neutrinos from supernovæ

Type II supernovæ (called SN in the following) have a spectrum with H lines

Figure 7: a) Regions of the parameter plane of neutrino oscillation allowed by the MSW effect for interpreting solar neutrino experiments (90 % C. L.) for the Bahcall and Pinsonneault (BP) and for the Turck-Chièze and Lopes (TCL) models. 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).

and correspond to very massive stars ($M > 8 M_\odot$), which evolve into red or blue supergiants; they become suddenly unstable and energy produced cannot balance gravity. Their core collapses within seconds before they explode, transforming most of their energy into neutrinos. The detection of these neutrinos is fundamental to understand the explosion mechanism.

The reader is referred to some excellent reviews, for example by Mochkovitch ⁴⁹, Arnett et al. ⁵⁰, Burrows ⁵¹ or Bahcall ²⁰ for more details, without forgetting the “empirical and analytic approach” of SN1987A by Bethe ⁵².

3.3.1. How (we think that) SN explode.

Massive stars ($M > 8 M_\odot$) live only few tens of million years. For a typical $20 M_\odot$ star, it takes 10×10^6 years to burn hydrogen into helium (mostly via the CNO cycle, since the central temperature is typically 100×10^6 K), 10^6 years to go from He to C and O, 300 years to produce Ne from C, 1 year to reach the Si, 2 days to obtain a Fe core. At this moment, the structure of the star is onion-like, going from H outside to the Fe core. When the core reaches the Chandrasekhar mass ($1.4 M_\odot$), it starts to collapse : no further nuclear energy can be generated and degenerate electron pressure can no longer counterbalance gravity. Then he explodes.

SN provide luminous ($\sim 10^{49}$ erg) and kinetic ($\sim 10^{51}$ erg) energy and large amount of neutrinos (order of 10^{53} erg as has been checked from the observation of SN1987A). Only the formation of a compact remnant, probably a neutron star (or a black hole for the more massive stars) can provide such a huge amount of energy.

Assuming that a $1.4 M_{\odot}$ neutron star of radius $R = 10$ km is formed, its binding energy, GM^2/R , is few times 10^{53} erg.

We now follow the description by Burrows⁵¹ with the corresponding schematic synopsis in figure 8. The unstable core of the progenitor has a radius of a few thousand kilometers, and is embedded in a star with a radius of about 3×10^8 km. Its initial temperature and density are about 5×10^9 K and 10^{10} g/cm³ respectively.

Figure 8: A schematic (not to scale) depicting the evolution of the core of a massive star ($20 M_{\odot}$) from core collapse to bounce and shock formation, to protoneutron star, to young, compact neutron star. Neutrino emission is indicated with ν . (From Burrows⁵¹.)

When the mass of the Fe core reaches the Chandrasekhar mass, the central density and temperature rise, which leads to electron capture ($e^- p \rightarrow n \nu_e$) and Fe photodesintegration. The entropy of the electron gas decreases and the core loses pressure support and implodes. As the collapse proceeds, the flow breaks into a subsonic inner core (about $0.6 M_{\odot}$) and a supersonic outer core (about $0.8 M_{\odot}$), separated by a sonic point. In less than one second, the subsonic inner core reaches nuclear densities, few 10^{14} g/cm³, and a nuclear phase transition between bound nuclei and free nucleons occurs. Before, relativistic electrons and ν_e dominate the pressure and cannot halt collapse. After, the repulsive nucleons dominate the pressure and the inner core stiffens dramatically. It rebounds as a unit into the unsuspecting supersonic outer core and a shock wave is generated at the interface.

Starting at a radius of about 20 km, a density of 10^{13-14} g/cm³, a mass of about $0.6 M_{\odot}$ and a speed near 10^{10} cm/s, the shock dissociates the outer mantle as it works its way out in mass and radius (a lot of ν 's of all species are produced, we will come back later). The expanding inner core energizes the shock wave and a protoneutron star is formed. At this stage, it continues to be fattened by the further accretion of outer core matter and is bounded by the shock wave. Either the shock continues undeterred into the outer stellar envelope (prompt mechanism), or it stalls, only to

be revived within hundreds of ms by neutrinos from the core (delayed mechanism).

Simulation processes generally fail to explain the prompt mechanism since the shock has not sufficient energy to make the star explode. The study of the delayed mechanism has been largely improved in the last years due to the use of multidimensional, instead of one-dimensional, simulation, thanks to the increase of the computing power⁵³. The understanding is not yet however complete and the observation of a large amount of neutrinos from a SN explosion in our Galaxy will greatly help for modelling.

The neutrino emission can be divided in three distinct periods : i) the infall and flash (at shock breakout); ii) the period of accretion until the explosion; iii) the neutronization and cooling of the protoneutron star. The corresponding neutrino luminosity is displayed in figure 9 and their mean energy in figure 10.

Figure 9: Neutrino luminosity during (a) the first second after shock breakout and (b) the first fifty seconds. (From Burrows et al.⁵⁴).

i) During the core collapse, ν_e produced by electron capture escape freely until trapping. They signal the initial neutronization of the core as it begins its transformation into a neutron star. Their mean energy is ≈ 15 MeV. The energy lost during the infall is $\approx 2 \times 10^{51}$ erg. After the formation of the shock material is heated and nuclei are dissociated into free nucleons. This leads to rapid captures on free protons, which produce ν_e , and to build up of a thermal distribution of neutrinos (ν_e , ν_μ and ν_τ , via $e^+e^- \rightleftharpoons \nu\bar{\nu}$ processes) at the post shock temperature. When the shock reaches the neutrinosphere, all these neutrinos escape within ≈ 5 ms. About 10^{51} erg in ν_e is lost from the capture on free protons, while ν_μ and ν_τ carry $\approx 0.5 \times 10^{51}$ erg, giving for the breakout luminosities $\approx 2 \times 10^{53}$ erg.s⁻¹ for ν_e and $\approx 10^{53}$ erg.s⁻¹ for ν_μ and ν_τ . The ν_e luminosities from infall and at breakout merge to reach a peak value of $\approx 6 \times 10^{53}$ erg.s⁻¹. After breakout, all neutrino spectra rapidly become thermal, with

Figure 10: Energy of the different neutrinos during the SN explosion.

temperatures of few MeV.

ii) After 10-30 ms the shock stalls and the infalling material flows throughout to be accreted by the hydrostatic core. The accretion luminosity is equally shared between all neutrino species. Its temperature (and E_ν) slowly increases. At the moment of explosion, the mantle is ejected and there is a sudden increase of both the luminosity and E_ν (see figure 10). The neutrino light curve and energy spectrum of a galactic SN would be of great help to decide between the prompt and delayed mechanisms. Possible oscillations (see figure 9) would reflect the dynamics of the protoneutron star.

iii) Accretion stops after explosion but at that time the amount of energy lost ($3 \cdot 5 \times 10^{52}$ erg) is only 10-20 % of the neutron star binding energy. The bulk of the energy will be released in a deleptonization and cooling phase which lasts a few seconds. Neutrinos interact with matter through scattering (all species) or absorption (ν_e only) processes. The duration of the cooling phase (few tenths of seconds) is controlled by the neutrino diffusion time scale.

Before SN1987A, the only information on SN was coming from their light curves which result from a convolution between the different energy sources and the process of diffusive transport through the envelope. Typical SN light curves show a) shock energy deposition in the envelope of the progenitor in the first days and b) the ^{56}Ni and ^{56}Co radioactivity (with their characteristic exponential decrease) which dominate in the first months after the explosion. The light curve of SN1987A has been largely studied, but the revolution came from the observation of its neutrinos.

3.3.2. Experimental observation of neutrinos from SN.

a) SN1987A.

February 23, 1987 is an historic date for (astro)physics. At 7.35 UT, about 20

Figure 11: a) Time sequence and electron energy of the SN1987A events observed by Kamioka (shaded circles) and IMB (open circles). b) Cumulative number of neutrinos from SN1987A as compiled by Mayle and Wilson ⁵⁶.

neutrinos produced 150 million years ago in the explosion of Sanduleak-69202, a super blue giant located in the Large Magellanic Cloud (LMC), were observed in ~ 10 seconds by the Kamiokande and IMB ⁵⁵ detectors.

Figure 11a displays the energy/time distribution of the 12 events seen by Kamioka and the 8 events seen by IMB (whose energy threshold is only about 20 MeV). The integrated number of ν 's as a function of time seen by the two experiments is shown in figure 11b. The arrow marks the transition from the initial period of very high luminosity (2s) to the later period of lower luminosity (in agreement avec model expectations).

At first order, the ν fluxes from SN are equally shared between ν_e , ν_μ , ν_τ and their antiparticles, as was seen on figure 10 (there are only slightly more ν_e as discussed previously). But the cross section for 10-20 MeV (anti)neutrinos is ~ 100 times larger for $\bar{\nu}_e$ ($\sigma(\bar{\nu}_e + p \rightarrow n + e^+) \approx 10^{-41} (E_\nu/10 \text{ MeV})^2 \text{ cm}^2$) than for other (anti)neutrinos which, at such energy, interact only elastically with electrons. This means that all the events seen by the detectors are most probably induced by $\bar{\nu}_e$, and that the Cerenkov light was due to positrons (these detectors cannot differentiate e^+ from e^-). Taking into account the experimental thresholds and the energy distribution of the $e^\pm$, the average energy of the incoming (anti)neutrinos is ~ 10 MeV. This induces a total neutrino energy of $\sim 3 \times 10^{53}$ erg, the expected binding energy of a neutron star.

b) The future of SN neutrino detection.

The list of the present or forthcoming detectors for SN neutrinos is given in table 4. The last column gives the expected number of events expected for a SN explosion in our Galaxy at a distance of about 10 kpc (i.e. ~ 5 times closer than SN1987A). The expected SN rate at such typical distance is several per century (controversial number, see for example ⁵⁷). Details of what can be observed and tested for such a SN in the major detectors can be found for example in Burrows et al. ⁵⁴.

Kamiokande has been replaced in 1996 by SuperKamiokande ²⁸. It will be sensitive

Table 4: Major detectors for SN neutrinos. The depth is in meters of water equivalent. Note that IMB (Ohio, USA) which greatly contributed to SN1987A has been since dismantled.

Detector	Location	Depth (m.w.e.)	Mass (tons) [fiducial]	target	Nb of events for a SN at 10 kpc
Kamiokande until 1996 ²⁷	Japan	2700	2140 [1200]	H ₂ O	350
SuperKamiokande > 1996 ²⁸	Japan	2700	50000 [25000]	H ₂ O	5000
SNO ³³ > 1997	Sudbury Canada	6000	1600 1000	D ₂ O	800
LVD ⁵⁸	Gran Sasso Italy	3300	1840 [600 now]	scintillator	400 [150 now]
MACRO ⁵⁹	Gran Sasso Italy	3300	600	scintillator	150
Baksan	Russia	850	330 [200]	scintillator	75

practically only to $\bar{\nu}_e$. SNO ³³, should start in 1997; the D₂O target allows it to be also sensitive to ν_μ and ν_τ . LVD ⁵⁸ is made of 190 modules arranged in five towers; each module contains about 9.6 tons of liquid scintillator and 8 scintillation counters; 2 towers are currently operating at Gran Sasso; MACRO ⁵⁹ is also using liquid scintillator and operating at Gran Sasso. The Baksan scintillator experiment which could have seen some neutrinos from SN1987A, is still operating in Caucasus.

The neutrino energy spectrum and the corresponding flux for a neutrino burst coming from a SN in our Galaxy has been shown in figure 4, together with the main other astronomical sources. On the same figure, with the same energy spectrum, but several orders of magnitude below in intensity is also displayed the faint diffuse neutrino background coming from all SN explosions since the beginning of the Universe (see Lagage ⁶⁰ which also shows that this flux is now dominated by the (anti)neutrinos coming from nuclear reactors below ~ 10 MeV).

3.4. Atmospheric neutrinos

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

Simple counting of daughters concludes that :

Table 5: Main results for atmospheric neutrinos.

Experiment	Detector type	$(\mu/e)_{\text{data}} / (\mu/e)_{\text{MC}}$	Exposure kton.y	Years
IMB	Cerenkov	$0.54 \pm 0.02 \pm 0.07$	7.7	1982-1991
Kamiokande (multi-GeV)	Cerenkov	$0.60 \pm 0.06 \pm 0.05$	7.7	1988-1995
		$0.57 \pm 0.08 \pm 0.07$	6.0	1988-1995
Soudan	calorimeter	$0.75 \pm 0.16 \pm 0.10$	2.9	1987-1993
Fréjus	calorimeter	$1.00 \pm 0.15 \pm 0.08$	2.0	1984-1988
Nusex	calorimeter	1.04 ± 0.25	0.40	1981-1986

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx \frac{2}{1} (\pm 5\%) \quad \text{and} \quad \frac{\nu}{\bar{\nu}} \approx 1 \quad (9)$$

Depending on the interaction point in the atmosphere, the distance traveled by the neutrino varies from 10 km to $1.3 \cdot 10^4$ 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 Kamiokande and IMB and calorimetric like Fréjus or Soudan, and the identification of electrons or muons is not the same. Low energy events are generally contained in the detector. The statistics is low, few hundred of events at maximum. A summary of the main results is found in table 5.

A significant deficit in the ratio is given by the Kamiokande experiment ⁶¹, which has the largest statistics, but it is difficult to reconcile with the result of the Fréjus 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 water target to a neutrino beam showing that they were able to separate with a sufficient accuracy the two types of neutrinos. Some possible systematic errors have been recently 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 the Kamiokande experiment showed that the neutron induced background was negligible ⁶². The situation has to be improved experimentally (and maybe theoretically with a better determination of the neutrino fluxes). In the time being, Kamiokande interprets this deficit as a possible neutrino oscillation with ν_μ transformed into ν_e or ν_τ (see figure 3), interpretation which has to be confirmed.

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 statistics is still low. The results of the MACRO experiment for example are compatible with the two scenarios (with and without oscillation).

This atmospheric neutrino anomaly will probably be clarified by SuperKamiokande which promised first results in 1997, and by the reactor experiments at Chooz and Palo Verde (except if the oscillation is a $\nu_\mu \rightarrow \nu_\tau$ oscillation), before we obtain the long baseline results.

For recent reviews on atmospheric neutrinos see for example reference ⁶³.

3.5. High energy neutrinos

This topic is excellently reviewed by F. Halzen in these proceedings ⁶⁴.

4. Puzzling experiments

We finally report briefly on two puzzling beam stop (low energy) experiments, LSND and KARMEN.

4.1. 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations ⁶⁵. The $\bar{\nu}_e$ is detected via the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ correlated with a 2.2 MeV γ coming from $np \rightarrow d\gamma$. 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 12) It is interpreted as a $\bar{\nu}_e$ appearance and there is still a small area in the $(\Delta m^2, \sin^2 2\theta)$ plane at $\sin^2 2\theta$ values of few 10^{-3} and Δm^2 above 1 eV^2 (see figure 3) which is not yet excluded by the other experiments, in particular KARMEN ⁶⁶. The analysis in the $\nu_\mu \rightarrow \nu_e$ channel is in progress.

Figure 12: Energy distribution for $\bar{\nu}_e$ events in the LSND experiment. Dashed line represents the expected background.

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

collaboration (see below) plans to improve its experiment to explore this puzzle ⁶⁶.

4.2. KARMEN

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. Neutrons are detected through a $Gd(n,\gamma)$ capture reaction. No evidence for neutrino oscillation has been found ⁶⁶, but analysis of the charged and neutral current reactions $^{12}C(\nu_e, e^-)^{12}N$ and $^{12}C(\nu, \nu')^{12}C^*$ reveals an anomaly in the time distribution after all the π^+ have decayed : the measured time constant for subsequent events differs substantially from the expected $2.2 \mu s$ (μ^+ lifetime); the kink in the time distribution presents an excess of 112 ± 32 events at $3.6 \mu s$ ^{66,67}. The authors suggest a speculative explanation : the delayed events could come from a slowly moving massive neutral particle produced in the beam stop. Further measurements are clearly needed ("wait and see").

After an upgrade of the detector, particularly the veto, the future of KARMEN is now to test the parameter space allowed by LSND, and to clarify the time anomaly.

5. Perspectives on neutrinos

The future of neutrinos is very rich. Many experiments are looking for neutrino masses or explore the Universe using neutrinos. Among the different present evidences for a neutrino mass, my personal point of view can be summarized as follows :

- a) the MSW effect as the solution of the solar neutrino problem is very attractive; the forthcoming results from SuperKamiokande (confirmation of the deficit, possible spectrum distortion) but especially of SNO (neutral current events and/or spectrum distortion) and Borexino (ν_{Be} deficit) will tell us within 3-4 years if it is the truth; for the time being, GNO, at Gran Sasso will substitute to GALLEX to monitor the ν_{pp} flux.
- b) the atmospheric neutrino problem should be clarified soon by SuperKamiokande and/or reactor experiments like Chooz;
- c) the puzzling phenomenon observed by LSND at Los Alamos will be probably killed by LSND itself or by KARMEN.

But if one believes in the three evidences, playing with the data and their errors, one can still interpret them simultaneously with the three neutrino flavours with (see ⁶⁸) or without (see ⁶⁹) maximal lepton mixing.

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 .

Three points to conclude : a) we need imagination of physicists to detect cosmological neutrinos; this is a real challenge; b) we can hope that the neutrinos from

a close supernova are already approaching our traps deep underground; LVD and MACRO at Gran Sasso, SuperKamiokande are ready; SNO will start soon; c) we would like that neutrinos constitute a "hot" component of dark matter; CHORUS and NOMAD, and later COSMOS should give the answer.

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