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PRESENT STATUS AND PROSPECTS OF NEUTRINO OSCILLATION EXPERIMENTS

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ABSTRACT

The solution of the long standing solar and atmospheric neutrino puzzles has led to the unambiguous confirmation that neutrinos oscillate and hence are massive. Several key experiments have contributed to clarify the experimental scenario. A wide programme is being executed and is planned for the next years, aimed at pinning down the oscillation parameters and at more sensitive measurements of the elements of the Pontecorvo, Maki, Nakagawa, Sakata (PMNS) mixing matrix. As far as accelerator neutrino experiments are concerned, further technological advances will be required for both beam facilities and detectors to realize the next generation of experiments that will address the issues of CP violation in the leptonic sector and of mass hierarchy. In this respect, we want to stress here the great potentialities of the LAr Time Projection Chamber (TPC) technology for future applications. The ICARUS R&D programme has demonstrated that the technology is mature and that one can built a large ($\sim$ 1 kton) LAr TPC with a fully industrial method. Nowadays one can conceive and design a very large mass LAr TPC with a mass of 100

kton by emploing a monolithic technology based on the use of industrial, large volume cryogenic tankers. Such a detector would be an ideal match for a Super-Beam, a Beta-Beam or a Neutrino Factory, allowing to execute, in addition to a rich accelerator neutrino physics programme, experiments on atmospheric, solar and supernova neutrinos, as well as sensitive searches for nucleon decay.

1 Introduction

We can schematically summarize our present knowledge on (massive) neutrinos by stating that

- There is evidence for three light neutrinos in Nature, as an outcome of the LEP experiments 1).
- Direct neutrino mass measurements have so far only yielded limits in the range of 1 eV^2 or less. Very stringent limits have also recently come from cosmological measurements 2). This reinforces our common believe that the nature and the characteristics of the fascinating neutrino are closely linked to cosmological and astrophysical subjects.
- Neutrino oscillation experiment with solar and atmospheric neutrinos have contributed to build up a solid evidence for neutrino oscillations, hence confirming that neutrinos are massive: this must be considered as the first compelling evidence for physics beyond the Standard Model of particles and interactions.
- Neutrino mixing is described by the so called PMNS 3 x 3 matrix. Two of the mixing angles are rather large (θ_{12} and θ_{23}) while the third is small or even null. The two Δm^2 experimental values confirm the smallness of the neutrino masses (see *e.g.* 3).)

More interesting and stimulating is the list of the 'unknowns'. First is the actual neutrino mass scale and even more the explanation of why neutrino masses are small as compared to the masses of the other fermions. The second question is why (two of) the mixing angles are large (differently from what happens for the quark mixing) and why the third angle is apparently small or equal to zero. Another issue is the neutrino mass hierarchy: is the tau-neutrino the heaviest? Is Δm^2_{23} positive or negative? These important questions can

Table 1: *Global fit of oscillation data (from* [3]*).*

Parameter	best fit value	3σ
Δm^2_{21} (10^{-5} eV^2)	7.9	7.2-9.1
Δm^2_{31} (10^{-3} eV^2)	2.3	1.4-3.3
$sin^2\theta_{21}$	0.3	0.23-0.38
$sin^2\theta_{23}$	0.5	0.34-0.68
$sin^2\theta_{13}$	0.002	<0.047

be addressed by studying so called matter effects (MSW), namely the effects occurring to neutrinos oscillating through matter [5]. Last but not least, there is the subject of CP violation in the neutrino sector. The PMNS matrix has a phase term that, if non zero, could cause CP violating effects, detectable *e.g.* by comparing oscillation results obtained with neutrinos and antineutrinos.

The answer to the above outstanding questions will likely keep neutrino physicists occupied for the next two decades, similarly to the time that has been required to go from the first signals of anomaly in the solar neutrino fluxes to the solid establishment of neutrino oscillations.

The present scenario is summarized in Table 1, where the results of a global fit of all oscillation data are presented [3]. Needless to say, we assume that mixing occurs among three active neutrinos (two Δm^2 and three mixing angles) and that, therefore, we do not take into account the so called LSND effect, that if real would naturally lead to the existence of a fourth (sterile) neutrino. The Fermilab MiniBoone experiment will soon clarify this issue [4].

From what we mentioned above, it is rather obvious what the tasks of future accelerator neutrino experiments will be, aimed at a deeper understanding of the physics of massive neutrinos:

- to observe ν_τ appearance: find the body after the murder;
- to know is there (some) room for a sterile neutrino: MiniBoone experiment and ν_μ disappearance;
- to measure the L/E dependence: atmospheric neutrinos and Wide Band Beam accelerator experiments (fixed L);
- to accurately measure the two Δm^2, θ_{12} and θ_{23}: is θ_{23} exactly $\pi/4$?

- to find the value of θ_{13} from P$(\nu_\mu \to \nu_e)$: benchmark measurement;
- to show MSW matter effects (without CP violation effects): mass hierarchy;
- to show CP violating effects (without matter effects): the ultimate goal?
- to be ready for the unexpected!: experiments may be running for long time.

In order to review the above experimental programme, we can start by briefly presenting the neutrino mixing matrix and some of its peculiar features.

The unitary mixing matrix, which can be parameterized as

$$U(\theta_{12},\theta_{13},\theta_{23},\delta) = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \quad (1)$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$, we get the freedom of the complex phase (physical only if $\theta_{13} \neq 0$).

For the interesting case of $\nu_\mu \to \nu_e$ oscillations and under the empirical assumptions (justified by the experimental results) that

- $\Delta m^2_{atm} >> \Delta m^2_{sol}$;
- L is comparable to the atmospheric oscillation length (~ 1000 km);
- the angle θ_{13} is small,

the general three-neutrino oscillation formula can be developed as a sum of terms

$$\begin{aligned} P\,(\nu_\mu \to \nu_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ &+8c_{13}^2 s_{13}s_{23}c_{23}s_{12}c_{12}\sin\Delta_{31}\left[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta\right]\sin\Delta_{21} \\ &-8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ &+4c_{13}^2 s_{12}^2\left[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right]\sin 2\Delta_{21} \\ &-8c_{13}^2 s_{13}^2 s_{23}^2 (1-2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] \end{aligned} \quad (2)$$

where $s_{ij}= sin\theta_{ij}$, $c_{ij}= cos\theta_{ij}$, $\Delta_{jk} \equiv \Delta m^2_{jk} L/4E_\nu$ and

$$a = 2\sqrt{2} G_F N_e E_\nu = 1.54 \times 10^{-4} Y_e \rho (g/cm^3) E_\nu (GeV) \tag{3}$$

with a is given in eV^2.

In the above formula the leading term is the first one. The third and fourth terms give CP conserving (small) contributions. The second term includes the CP violating effects due to $sin\delta$. The last term includes matter effects, due to the passege of the oscillating neutrino through matter. One can notice that the θ_{13} angle is the 'link' between the atmospheric and the solar term. As we will see later, this term has great importance for future studies: if it is exactly zero there will be no CP violating effects and the global oscillation phenomenology would certainly be poorer.

The above relation reduces to the following one if one restricts to vacuum oscillations computed to leading order

$$P\,(\nu_\mu \to \nu_e) = sin^2 2\theta_{13} \times sin^2\theta_{23} \times sin^2\Delta_{23} \tag{4}$$

2 Present generation of accelerator-nutrino oscillation experiments

The K2K experiment in Japan can be considered as the'mother' of all long baseline (LBL) experiments (6), designed to be tuned to the atmospheric neutrino oscillation parameters. The Super-Kamiokande (7) detector is hit by the low energy neutrinos ($\sim$ 1 GeV) from KEK after a travel of about 250 km. The L/E of the experiment is such to provide sensitivity to the oscillation parameter of the atmospheric neutrino signal. Oscillation are searched for with a ν_μ disappearance experiment profiting of a series of near detectors used for flux normalization and background estimates. A comparison of near/far event rates and an analysis of the energy spectrum distortion are exploited to infer the oscillation signal. The latest results confir the results obtained by Super-Kamiokande exposed to atmospheric neutrinos, indicating $1.7 < \Delta m^2 < 3.5$ eV^2 and $sin^2 2\theta = 1$ at the 90% CL. The oscillation hypothesis is confirmed at nearly the 4σ level.

The next LBL experiment to come on duty (2005) will be the MINOS detector (8) in Minnesota in the NuMI neutrino beam from Fermilab, 730 km away. Also in this case, a ν_μ disappearance search will be performed. The far detector is made of magnetized iron disks and scintillator strips, for a total mass of about 5400 ton. MINOS should collect 2500 ν_μ charged current events per year. The main goal of the experiment will be the narrowing down of the errors on $sin^2\theta_{23}$ and Δ_{23}, needed to determine $sin^2 2\theta_{13}$, as shown in (4). Given its ability in discriminating electrons from muons, MINOS will also provide some sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations, and hence directly on $sin^2 2\theta_{13}$. In four years of running (by 2010) the existing limit of 0.14 from the CHOOZ reactor experiment 9) should be improved to about 0.06 8).

By 2006 the CERN-to-LNGS CNGS neutrino beam will be commissioned. In this case, we will deal with high energy neutrinos (10-20 GeV). This is needed to be well above threshold for τ production, as required to allow for a $\nu_\mu \rightarrow \nu_\tau$ appearance search, following the indications from the atmospheric neutrino measurements largely favoring this oscillation channel. Together with the ICARUS experiment 10) that we will discuss later, the dedicated OPERA experiment 11) is being built at LNGS, exploiting a novel application of nuclear emulsions for the direct detection of the short (less than 1 mm long) τ track. Although with small statistics (less than 20 events in 5 years of running), thanks to the very low expected background ($<$ 1 event) OPERA should be capable to unambiguously confirm the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis.

3 The next goal: the measurement of θ_{13}

From what said in the Introduction, an important role in the neutrino oscillation framework is played by the θ_{13} angle. On the one hand, it is the link between the atmospheric and the solar oscillation parameters, and on the other hand, only if it is non zero, one could expect a non vanishing CP violating phase in the mixing matrix.

A determination of θ_{13} can be accomplished by measuring $\nu_\mu \rightarrow \nu_e$ oscillations according to (4). This measurement can be well performed with accelerator neutrino experiments, although the present best limit has been set by the CHOOZ reactor experiment. The main experimental limitations are given by the prompt ν_e contamination in the ν_μ beams, by the π_0 background capable to fake the production of electrons, and by the additional background of low energy muons and pions that can be misidentified as electrons. Obviously, the relevance of the above backgrounds strongly depends upon the parameters of the neutrino beam and on the adopted detection technique. It is worth to mention that the use of the future Beta-Beams providing pure ν_e beams could allow to perform $\nu_e \to \nu_\mu$ appearance experiments, by far less demanding from the detection point of view.

In any case, given the smallness of the effect ($< 5\%$), the use of next generation high-intensity beam facilities is a must. In particular, one usually thinks of Super-Beams, namely conventional accelerator neutrino beams fed by high-intensity proton accelerators able to increase by factors 10-100 the presently achievable neutrino intensities.

Likely, the first Super-Beam to be operational by 2009 will be once more in Japan, for the T2K experiment 12). The far detector, at least in the first phase of operation, will still be Super-Kamiokande, placed about 300 km away from Tokay. A 0.8 MW, 50 GeV Proton Synchrotron will produce a high-intensity, low-energy neutrino beam. About 3000 ν_μ charge current events per year will be produced in Super-Kamiokande, namely one order of magnitude increase with respect to K2K. The detector will be placed about 2 degrees off-axis with repect to the proton beam direction, to allow for an increase of the intensity around the neutrino energy optimizing the L/E ratio, and in parallel a suppression of the high energy tail of the spectrum, so that to reduce most of the backgrounds. Great care will have to be devoted to the near detectors and to the normalization procedure, since already in K2K the main systematic error is given by the differences in the near/far detector energy spectra. The experiment will perform both dispappearance and appearance oscillation measurements. The expected sensitivity in the ν_e appearance measurement of $sin^2 2\theta_{13}$ corresponds to a factor 20 improvement compared to the CHOOZ limit.

Other projects focusing on the key measurement of the θ_{13} angle are planned of being discussed. We can mention, for example, the Noνa experiment that has been proposed to run off-axis in the NuMI beam, starting around 2010 13). The experimental technique is based on a low-density (particle board and liquid scintillator), high-mass (50 kton) detector capable of a good electron identification. The rather long distance from the neutrino source (about 800 km) makes matter effect detectable. After its firts phase of operation in the existing NuMI beam, the experiment would certaily benefit from the envisoned Fermilab Super-Beam, centered around a new proton driver. Under these circumstances the experiment would seriously compete with the T2K project, achieving a 3σ sensitivity to $sin^2 2\theta_{13}$ around 0.006.

4 More distant future: experiments on CP violation in the neutrino sector

After the next round of experiments aiming at the measurement of $sin^2 2\theta_{13}$, in the fortunate hypotesis of success (non zero angle detected) the search for CP violating effects in the neutrino sector will be opened. A sensible method to pin down CP violating effects is the measurement of the so called asymmetry, shown below for vacuum oscillations

$$A_{CP} = \frac{P(\bar{\nu}_e \to \bar{\nu}_\mu) - P(\nu_e \to \nu_\mu)}{P(\bar{\nu}_e \to \bar{\nu}_\mu) + P(\nu_e \to \nu_\mu)} \sim \frac{sin^2\theta_{12}}{sin\theta_{13}} \times sin\delta \times sin\frac{\Delta m^2_{12} L}{4E} \qquad (5)$$

From this relation it first turns out that larger effects are expected for larger values of Δm^2_{12} and $sin^2\theta_{12}$. That seems to be the case, being the LMA solution the preferred one for solar neutrino oscillations 3). One also sees that a small value of $sin\theta_{13}$ is preferable. However, this latter requirement is somehow in conflict with the fact that the oscillation probability increases with $sin^2 2\theta_{13}$, as indicated by Equation (4). This 'conflict' has a clear impact on the detector design: if θ_{13} is small one is confronted with low statistics and large asymmetry; if θ_{13} is large one has the opposite.

The above described measurements will be likely accomplished with a further generation of beam facilities and detectors. As far as the beam are concerned, we already mentioned Super-Beams, Beta-Beams and (for a more distant future!) Neutrino Factories. Without entering in the details about these facilities, we insist once more on the fact that given the expected smallness of CP violating and matter effects high intensity facilities will be mandatory.

A global (physics driven) optimization of the neutrino beam parameters, of the detector technology and of its location will be required. As an example, we can mention two extreme approaches for the choice of L/E (Equation (6)): one could match this quantity to the first (or second) oscillation maximum with both a 'long L-high E' or a 'short L-low E' configuration.

The first case is well interpreted by the proposed projects at Fermilab and Brookhaven 14). In both cases, one envisages neutrino energies of a few GeV matching baselines of 1000 km or more. CP violating effects would then increase with the long L ($3/\pi/2$ vs $\pi/2$) and a second maximum location would also increase the detectable asymmetry thanks to matter effects (E_{max2}/E_{max1}). The second choice, *e.g.* as the one proposed for the discussed beam from CERN to Frejus, has the advantage of using neutrinos with energies below most of the competing background thresholds. However, for neutrino energies as low as a few hundreds of MeV one has to deal with backgrounds from atmospheric neutrinos and with the effect of Fermi momentum, limiting the resolution for muon events. Low energy has also a dramatic effect on the duration of the antineutrino runs (needed to asses the CP asymmetry), due to the smallness of the corresponding cross section.

On the other hand, matter effects can well induce degeneracies in the determination of the experimental results. For this reason one can anticipate that experiments with different baselines/energies/detection techniques might be required to fully exploit complementarity and disentangle the above degeneracies.

Concerning the apparatuses, a factor ten-twenty mass increase with respect to Super-Kamiokande is usually considered as a benchmark detector choice. Examples are given by the Hyper Kamiokande 15) or UNO 16) detectors. We believe that the main reason for this is the long series of outstanding results obtained with Super-Kamiokande, that successfully exploits the water Cerenkov detection technique. Moreover, one can extrapolate the cost to the larger mass detector with good confidence, that then appears to be a sufficiently cost effective solution. The detection method works rather well for low energy quasi-elastic (1-ring) neutrino events. The required electron/π_0 rejection can be efficiently accomplished if the two gammas are well separated. However, some confusion may arise in the muon/pion separation at low energy and the detection threshold cannot be realistically reduced below 5 MeV for the 'working hypothesis' of a 40% PMT coverage. In addition, alternative photodetector devices might require quite a long R&D work. Last but not least, the relatively low-density and, hence, large-volume of a 500-1000 kton detector implies a huge cavern with a complex and costly excavation work.

For the above reasons, one is led to think about possible alternative or complementary approaches. Among these, the liquid Argon TPC technique is certainly a viable and realistic option for a next generation neutrino and astroparticle physics experiments [17].

5 Liquid Argon TPC detectors: a technique for future neutrino experiments?

The technology of the Liquid Argon Time Projection Chamber (LAr TPC) was conceived and proposed by C. Rubbia in 1977 [18] as a tool for high accuracy imaging of massive detector volumes. The operating principle of the LAr TPC is based on the fact that in highly purified LAr ionization tracks can be transported undistorted by a uniform electric field over distances of the order of meters. Imaging is provided by wire planes placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons. The main technological challenges of the detection technique are the liquid Argon purification, the operation of wire chambers in cryogenic liquid without charge amplification, the very low-noise analog electronics, and the continuous wave-form recording and digital signal processing.

The feasibility of the technology has been demonstrated by the extensive ICARUS R&D programme, culminated with the realization and the surface test with cosmic-rays of the 600 ton ICARUS T600 detector [19]. The success of the fully industrial construction of the T600 module motivated and justified the idea of cloning the detector to reach the 3000 ton mass scale for experiments at LNGS. Here, the T3000 modularity was not imposed by the LAr TPC technique itself but it was an implementation choice motivated by the boundary conditions of the LNGS laboratory and by the requirement to build the detector outside of the underground hall.

Having at disposal the mature technique developed in the context of the ICARUS programme, physics is today calling for at least two applications at two different mass scales [17] and with a high degree of interplay and synergy: on the one hand, future precision studies of neutrino interactions and near stations for long baseline beam experiments will need detectors in the range of ~ 100 ton. On the other hand, ultimate nucleon decay searches and high statistics astrophysical and accelerator neutrino experiments will require very large masses, of the order of 100 kton, able to effectively compete with the large mass water Cerenkov detectors mentioned in the previous Section.

6 A 100 kton Liquid Argon TPC detector with charge imaging, scintillation and Cerenkov light readout

The possibility to construct and operate a very large LAr TPC can be considered a complex technical task. A single LAr volume is the most attractive solution from the point of view of construction, operation and cryogenics, and is to be favored over the modular approach. The basic design features of the detector can be summarized as follows 17)

1. Single 100 kton boiling cryogenic tanker at atmospheric pressure for a stable and safe equilibrium condition (temperature is constant while Argon is boiling). The evaporation rate is small (less than 10^{-3} of the total volume per day given by the favorable area-to-volume ratio) and is compensated by refilling of the evaporated Argon volume.
2. Charge imaging, scintillation and Cerenkov light readout for a redundant event reconstruction. This is a clear advantage over alternative detectors operating with only one of these readout modes.
3. Charge amplification to allow for very long drift paths. The detector runs in bi-phase mode. In order to allow for drift lengths as long as $\sim$ 20 m, which provides an economical way to increase the volume of the detector with a constant number of channels, charge attenuation will occur along the drift due to attachment to the remnant impurities present in the LAr. This effect is compensated with charge amplification near the anodes located in the gas phase.
4. Absence of magnetic field, although this possibility might be considered at a later stage, *e.g.* in conjunction with a future Neutrino Factory.

The cryogenic features of the above design are based on the industrial know-how in the storage of liquefied natural gases (LNG, $T \simeq 110$ K at 1 bar), which developed in the last decades driven by the petrochemical industry. The technical problems associated to the design of large cryogenic tankers, their construction and safe operation have already been addressed and engineering problems have been solved by the petrochemical industry. The current state-of-the-art contemplates cryogenic tankers of 200000 m^3 and their number in the world is estimated to be $\sim$ 300 with volumes larger than 30000 m^3. LNG tankers are always of double-wall construction with efficient but non-vacuum insulation between the walls. Large tankers are of low aspect ratio (height to width) and cylindrical in design with a domed roof.

The detector discussed here is characterized by the large fiducial volume of LAr included in a tanker with external dimensions of 40 m in height and 70 m in diameter. A cathode located at the bottom of the inner tanker volume creates a drift electric field of the order of 1 kV/cm over a distance of about 20 m. In this field configuration ionization electrons are moving upwards while ions are going downward. The electric field is delimited on the sides of the tanker by a series of ring electrodes (race-tracks) placed at the appropriate potential by a voltage divider.

The tanker contains both liquid and gas Argon phases at equilibrium. Since purity is a concern for very long drifts, we assume that the inner detector could be operated in bi-phase mode: drift electrons produced in the liquid phase are extracted from the liquid into the gas phase with the help of a suitable electric field and then amplified near the anodes in proportional mode. In order to amplify the extracted charge one can consider various options: amplification near thin readout wires, GEM, or LEM 17). Gain factors of 100-1000 are achievable in pure Argon.

After a drift of 20 m at 1 kV/cm the electron cloud diffusion reaches the size of 3 mm, corresponding to the envisaged wire readout pitch. If one assumes that the reachable electron lifetime is at least $\tau \simeq 2$ ms, as obtained in ICARUS T600 detector, one then expects an attenuation of a factor ~ 150 over the distance of 20 m. We remind that this attenuation (compensated by the amplification) will not introduce any detection inefficiency, given the value of ~ 6000 ionization electrons/mm produced along a *m.i.p.* track in LAr.

In addition to charge readout, we envision to locate PMTs around the inner surface of the tanker. Scintillation and Cerenkov light can be readout independently. LAr is a very good scintillator with about 50000 γ/MeV. However, this light is essentially distributed around a line at $\lambda = 128$ nm and, therefore, a PMT wavelength shifter (WLS) is required. Cerenkov light from penetrating muon tracks has been successfully detected in a LAr TPC. Since water and liquid Argon have very similar Cerenkov light emission properties and also similar physical properties in terms of radiation length, interaction length, etc.

The potential of future LAr detectors anticipate a large physics programme ranging from neutrino physics with artificial beams or astrophysical neutrinos, to the search for nucleon decay. For more information we refer to $^{17)}$ and references therein.

The operation of a large 100 kton LAr apparatus in a neutrino Super-Beam advantageously profits from the very good granularity provided by the technique. In particular, the search for $\nu_\mu \to \nu_e$ events is very clean owing to the excellent e/π^0 separation. The imaging of the events and the high energy resolution in the LAr TPC make the study of Beta-Beams very attractive, in particular for the possibility to have separately pure ν_e and $\bar{\nu}_e$ beams. Good $\mu/\pi^\pm$ discrimination is important in order to suppress the neutral current background with a charged leading $\pi^\pm$. The combination of the information from the imaging (tracking and energy) with the Cerenkov light could provide adequate particle muon/pion separation.

In order to fully address the oscillation processes at a Neutrino Factory, the ideal detector should be capable of identifying and measuring all three charged lepton flavors produced in charged current interactions and of measuring their charges to discriminate the incoming neutrino helicity. Embedding the volume of Argon into a magnetic field would not alter the imaging properties of the detector and the measurement of the bending of charged hadrons or penetrating muons would allow a precise determination of the momentum and a determination of their charge. A field of 0.1 T will allow to discriminate with $> 3\sigma$ the charge for tracks longer than 4 m. The ability to measure electron and muon charges is the only way to address T-violation, since it implies the comparison between the appearance of ν_μ ($\bar{\nu}_\mu$) and $\bar{\nu}_e$ (ν_e) in a beam of stored μ^+ (μ^-) decays as a function of the neutrino energy.

The astrophysical neutrino physics programme is naturally very rich for a 100 kton LAr observatory. One expects about 10000 atmospheric neutrinos per year and about 100 ν_τ charged current event per year from ν_μ oscillations. These events, given the excellent imaging capabilities of the LAr TPC, will provide an unbiased sample of atmospheric neutrinos with unprecedented resolution. Solar neutrinos provide 320000 events per year with electron recoil energy above $\sim$5 MeV. This will give the possibility to make precision measurements of the solar neutrino flux and to study possible short and long term variations. A galactic SN-II explosion at 10 kpc yields about 20000 events.

Sensitivity to extragalactic supernovae should also be possible as well as to relic SN neutrino fluxes. A unique feature of the LAr TPC is the accessibility to several independent detection channels which have different sensitivities to different neutrino flavors.

Last but not least, direct evidence for GUT and baryon number violation represents one of the outstanding goals of particle physics. Nucleon decay searches require a very good knowledge of the backgrounds induced by atmospheric neutrinos. A target of 100 kton = 6×10^{34} nucleons yields a sensitivity for protons of $\tau_p/Br > 10^{34}$ years $\times$ T(yr)$\times\epsilon$ at the 90% C.L. in the absence of background. This means that lifetimes in the range of 10^{35} years can be reached within 10 years of operation. Channels like $p \to \nu K$ have been shown to be indeed essentially background free.

7 Conclusions

The solution of the long standing solar and atmospheric neutrino problems has led to the unambiguous confirmation that neutrinos oscillate and hence are massive. Several key experiments have contributed so far to the building up of the oscillation scenario. A wide programme is being executed and is planned for the next years, aimed at more sensitive measurements of the elements of the PMNS mixing matrix.

As far as accelerator neutrino experiments are concerned, further technological advances will be required for both the beam facilities and the detectors to realize the next generation of experiments addressing the issues of CP violation in the leptonic sector and of mass hierarchy.

The LAr TPC technology, whose basic R&D work has been successfully conducted by the ICARUS Collaboration, has great potentials for new generation neutrino experiments. In particular, a large, 100 kton device could effectively compete with giant 500-1000 kton water Cerenkov detectors being proposed for future precision studies of the neutrino mixing matrix and for nucleon decay searches. This 100 kton LAr TPC would provide the widest output for accelerator and astroparticle physics. Coupled to future Super-Beams, Beta-Beams or Neutrino Factories it could greatly improve our understanding of the mixing matrix in the lepton sector with the goal of measuring the CP phase, and in parallel it would allow to conduct astroparticle experiments of unprecedented sensitivity.

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