MEMPHYS : A large scale water Čerenkov detector at Fréjus

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Abstract

A water Čerenkov detector project, of megaton scale, to be installed in the Fréjus underground site and dedicated to nucleon decay, neutrinos from supernovae, solar and atmospheric neutrinos, as well as neutrinos from a super-beam and/or a beta-beam coming from CERN, is presented and compared with competitor projects in Japan and in the USA. The performances of the European project are discussed, including the possibility to measure the mixing angle θ_{13} and the CP-violating phase δ.

Contents

1 Motivations

There is a steady 25 year long tradition of water Čerenkov observatories having produced an incredibly rich harvest of seminal discoveries. The water Čerenkov movement was started in the early 80's by the scientists searching for proton decay. It fulfilled indeed this purpose by extending the proton decay lifetimes a few orders of magnitude. Furthermore, water Čerenkov's, through a serendipitous turn, as frequently happens in physics, have also inaugurated:

- particle astrophysics through the detection of the neutrinos coming from the explosion of the supernova 1987a by IMB and Kamioka, acknowledged by the Nobel prize for Koshiba
- the golden era of neutrino mass and oscillations by discovering hints for atmospheric neutrino oscillations while at the same time confirming earlier solar neutrino oscillation results.

The latest in the water Čerenkov series, the well known Super-Kamiokande, has now given strong evidence for a maximal oscillation between ν_μ and ν_τ, and several projects with accelerators have been designed to check this result. The results of the K2K experiment confirm the oscillation, and other experiments (MINOS in the USA, OPERA and ICARUS at Gran Sasso) should refine most of the oscillation parameters by 2010.

More recently, after the results from SNO and KamLAND, a solid proof for solar neutrino flavour oscillations governed by the so-called LMA solution has been established. We can no longer escape the fact that neutrinos have indeed a mass, although the absolute scale is not yet known. Furthermore, the large mixing angles of the two above-mentioned oscillations and their relative frequencies open the possibility to test CP violation in the neutrino sector if the third mixing angle, θ_{13}, is not vanishingly small (we presently have only an upper limit at about 0.2 on $\sin^2(2\theta_{13})$, provided by the CHOOZ experiment). Such a violation could have far reaching consequences, since it is a crucial ingredient of leptogenesis, one of the presently preferred explanations for the matter dominance in our Universe.

The ideal tool for these studies is thought to be the so-called neutrino factory, which would produce through muon decay intense neutrino beams aimed at magnetic detectors placed several thousand kilometers away from the neutrino source.

However, such projects would probably not be launched unless one is sure that the mixing angle θ_{13}, governing the oscillation between ν_μ and ν_e at the higher frequency, is such that this oscillation is indeed observable. This is why physicists have considered the possibility of producing new conventional neutrino beams of unprecedented intensity, made possible by recent progress on the conception of proton drivers with a factor 10 increase in power (4 MW compared to the present 0.4 MW of the FNAL beam). While the present limit on $\sin^2(2\theta_{13})$ is around 0.2, these new neutrino "superbeams" would explore $\sin^2(2\theta_{13})$ down to $2 \cdot 10^{-3}$ (i.e a factor 100 improvement on the ν_μ - ν_e oscillation amplitude).

European working groups have studied a neutrino factory at CERN for some years, based on a new proton driver of 4 MW, the SPL. Along the lines described above, a subgroup on neutrino oscillations has studied the potentialities of a neutrino superbeam produced by the SPL. The energy of produced neutrinos is around 300 MeV, so that the ideal distance to study ν_μ to ν_e oscillations happens to be 130 km, that is exactly the distance between CERN and the existing Fréjus laboratory. The present laboratory cannot house a detector of the size needed to study neutrino oscillations, which is around 1 million cubic meters. But the recent decision to dig a second gallery, parallel to the present tunnel, offers a unique opportunity to realize the needed extension for a reasonable price.

Due to the schedule of the new gallery, a European project would be competitive only if the detector at Fréjus reaches a sensitivity on $\sin^2(2\theta_{13})$ around 10^{-3}, since other projects in Japan (T2K phase 1) and USA (NoVA) will have reached 10^{-2} by 2015. The working group has then decided to study directly a water Čerenkov detector with a mass approaching 1 megaton, necessary to reach the needed sensitivity. This detector has been nicknamed MEMPHYS (for MEgaton Mass PHYSics). Its study has benefited from a similar study by our American colleagues, the so-called UNO detector with a total mass of 660 kilotons. Simulations have shown that the sensitivity on $\sin^2(2\theta_{13})$ at a level of 10^{-3} could indeed be fulfilled with MEMPHYS.

This version of the project as two competitors, since japanese and american physicists have their own project, with similar potentialities. But owing to a new idea recently proposed by Piero Zucchelli, the european project could have a unique characteristics which would make it very appealing. This idea is to send towards Fréjus, together with the SPL superbeam, another kind of neutrino beam, called beta beam, made of ν_e or $\overline{\nu}_e$ produced by radioactive nuclei stored in an accumulation ring. CERN has a very good expertise on the production and acceleration of radioactive nuclei. Studies show that such beams would reach performances even better than those of the SPL on the oscillation between ν_e and ν_μ , with a sensitivity on θ_{13} down to half a degree, with a factor four gain. But the main point is that both beams, if run simultaneously, would allow to study the violation of CP symmetry in a much more efficient and redundant way than when using only the SPL beam. This peculiarity, which would be a CERN exclusivity, would give a considerable bonus to our project concerning neutrino studies, since it could reach sensitivities on CP violation as good as those of a neutrino factory for $\sin^2(2\theta_{13})$ above $5 \cdot 10^{-3}$.

As mentioned in the beginning, such a detector will not only do the physics of neutrino oscillations, but would also address equally fundamental questions in particle physics and particle astrophysics.

In particular, such a detector could reach a sensitivity around 10^{35} years on the proton lifetime, which is precisely the scale at which such decays are predicted by most supersymmetric or higher dimension grand unified theories, thus giving the hope for a fundamental discovery.

Such a detector would also bring a wealth of information on supernova explosions: it would detect more than 10^5 neutrino interactions within a few seconds if such an explosion occurs in our galaxy, and would observe a statisticaly significant signal for explosions at distances up to 1 Mpc, and provide a supernova trigger to other astroparticle detectors (gravitational antennas and neutrino telescopes). For galactic supernova explosions, the huge available statistics would give access to a detailed description of the collapse mechanism and neutrino oscillation parameters. In addition, the huge mass of the detector could allow to detect for the first time the diffuse neutrinos from past SN explosions.

The proposed detector is indeed a multipurpose detector addressing several issues of utmost importance.

2 Megaton Physics

2.1 Proton decay

Proton decay is one of the few predictions of Grand Unified Theories that can be tested in low-energy experiments. Its discovery would definitely testify for a more fundamental structure beyond the Standard Model.

In the past twenty years, the first generation (IMB, Fréjus, Kamiokande) and second generation (Super-Kamiokande) proton decay experiments have already put stringent lower limits on the partial proton lifetimes, qualitatively ruling out non-supersymmetric $SU(5)$ theories (first generation) and the minimal supersymmetric $SU(5)$ theory (second generation). A megaton-scale water Čerenkov detector would improve further the experimental sensitivity to proton decay by more than one order of magnitude and allow to probe non-minimal $SU(5)$ models as well as other types of GUTs, such as $SO(10)$, flipped $SU(5)$ and higher-dimensional GUTs. Indeed, recent experimental and theoretical progresses point towards smaller values of the partial lifetime of the proton into $\pi^0 e^+$, implying that this decay mode – the most model-independent one – is not out of reach, contrary to previous expectations. Using the new, more accurate lattice calculation of the nucleon decay matrix element one can estimate $\tau(p \to \pi^0 e^+) \approx 10^{35}\,\mathrm{yrs}\,(M_X/10^{16}\,\mathrm{GeV})^4\,((1/25)/\alpha_{GUT})^2$, where M_X is the mass of the superheavy gauge bosons mediating proton decay, $\alpha_{GUT} \equiv g_{GUT}^2/4\pi$ and g_{GUT} is the value of the GUT gauge coupling at the unification scale. This is to be compared with the present Super-Kamiokande lower limit ($5 \times 10^{33}\,\mathrm{yrs}$), and with the expected sensivity of a megaton water Čerenkov detector ($10^{35}\,\mathrm{yrs}$ after 10 years of data taking for MEMPHYS).

The dominant decay channel in supersymmetric GUTs, $p \to K^+\bar{\nu}$, is much more model-dependent. The corresponding decay rate indeed depends on the couplings and masses of the supersymmetric partners of the heavy colour-triplet Higgs bosons, and on the details of the sparticle spectrum. The effective triplet mass, in particular, is extremely dependent on the GUT model. In many models, one finds an upper limit $\tau(p \to K^+\bar{\nu}) \leq \mathrm{few}\,10^{34}\,\mathrm{yrs}$ [1][2][3], to be compared with the present Super-Kamioka nde lower limit ($1.6 \times 10^{33}\,\mathrm{yrs}$), and with the expected sensivity of a megaton water Čerenkov detector ($2 \times 10^{34}\,\mathrm{yrs}$ after 10 years for MEMPHYS).

There are many more decay channels that could be accessible to a megaton water Čerenkov detector. The measurement of several partial lifetimes would allow to discriminate between different Grand Unified models, at a time when, after several years of LHC running, the supersymmetry landscape will be drastically clarified, through discovery or severe exclusion limits. Therefore the predictions of proton lifetime, in constrained or more general supersymmetric models, will be sharpened even further.

2.2 Supernovae

The core collapse supernovae are spectacular events which have been theoretically studied for more than three decades. After explosion the star loses energy, mainly by neutrino emission, and cools down, ending as a neutron star or a black hole. Many features of the collapse mechanism are indeed imprinted in the neutrinos released during the explosion.

At the same time, a galactic supernova would give particle physicists the occasion to explore the neutrino properties on scales of distance up to 10^{17} km and of time up to $\sim 10^5$ years and at very high density. The detected signal from a supernova explosion depends on the structure of the neutrino mass spectrum and lepton mixing. Therefore, in principle, studying the properties of a supernova neutrino burst one can get information about the values of parameters relevant for the solution of the solar neutrino problem, the type of the mass ordering (the so-called mass hierarchy), the mixing parameter $\sin^2\theta_{13}$, the presence of sterile neutrinos and new neutrino interactions.

It is generally believed that core-collapse supernovae have occurred throughout the Universe since the formation of stars. Thus, there should exist a diffuse background of neutrinos originating from all the supernovae that have ever occurred. Detection of these diffuse supernova neutrinos (DSN) would offer insight about the history of star formation and supernovae explosions in the Universe.

Now the requirements for a detector are to be very massive, located underground, to stay in operation for at least 20 years and to be equipped with a real time neutrino detection electronics with a threshold around 10 MeV. For those reasons a megaton water Čerenkov detector with a fiducial volume around 450 kt is a good choice. Such a detector would detect $\sim 10^5$ events from a galactic stellar collapse, and of the order of 20 events from a supernova in Andromeda galaxy, which is one of the closest to our Milky way. The large mass of such a detector compared to other proposed and existing facilities means that the sample collected will outnumber that of all other detectors combined. The general and relative performances are summarized in section 4.2.

All types of neutrinos and anti-neutrinos are emitted from a core-collapse supernova, but not all are equally detectable. The $\bar{\nu}_e$ is most likely to interact in a water Čerenkov detector. Three main neutrino signals would be detected, each one yielding unique information:

1. Inverse beta decay events (89%) allowing for a good determination of the time evolution and energy distribution of the neutrino burst. The potentials would be enhanced by the detection of the neutron with the addition of a small mount of Gadolinium [4].

2. Neutral current events involving ^{16}O (8%), which are sensitive to the temperature of the neutrino spectrum.

3. Directional elastic scattering events from $\nu_x + e^-$ and $\bar{\nu}_x + e^-$ ($\sim 3\%$). These events provide the direction of the supernova within ± 1 degree.

2.3 θ_{13} and CP violation in oscillations

In the recent years, a series of experiments have provided strong evidence for oscillations of solar and atmospheric neutrinos, and have started to precisely constrain the associated parameters Δm^2_{23}, Δm^2_{12}, θ_{23} and θ_{12}. The third mixing angle θ_{13} is still unknown: all we have is an upper bound of $\theta_{13} \leq 13^\circ$ coming from the CHOOZ experiment [5]. Its measurement, as well as the determination of the sign of Δm^2_{23} and therefore of the type of mass hierarchy, is crucial for discriminating between different neutrino mass and mixing scenarios. Moreover a precise determination of the PMNS matrix (which contrary to the CKM matrix is free from hadronic uncertainties) would put very severe constraints on models of fermion masses, including realistic GUT models, and thus shed some light on the underlying flavour theory. A neutrino super-beam from the CERN SPL to a megaton water Čerenkov detector located at Fréjus would allow to make a significant progress in this programme, reaching in particular a sensitivity to $\sin^2(2\theta_{13})$ close to 10^{-3} and close to $2 \cdot 10^{-4}$ with a Beta-beam (and $1 \cdot 10^{-4}$ with both Super-beam and Beta-beam), see section 4.3.

Due to its sensitivity to θ_{13}, a megaton water Čerenkov detector would also be sensitive to the CP violating phase δ in a large portion of the $(\Delta m^2_{12},\, \theta_{13})$ parameter space. Establishing CP violation in the lepton sector would represent a major progress in particle physics, since CP violation has only been observed in the quark sector so far. Moreover, CP violation is a crucial ingredient of leptogenesis, a mechanism for creating the matter-antimatter asymmetry of the Universe which relies on the out-of-equilibrium decay of heavy Majorana neutrinos. Although the phase involved in oscillations is generally distinct from the phase responsible for leptogenesis, the measurement of a nonzero δ would be a strong indication that leptogenesis may be at the origin of the baryon asymmetry [6]. Indeed, standard electroweak baryogenesis would require a very light Higgs boson, which is now excluded by LEP, and only a small window remains for supersymmetric electroweak baryogenesis. Another necessary ingredient of leptogenesis is the existence of Majorana neutrinos, which could be established by a positive signal in future neutrinoless double beta decay experiments.

3 Underground laboratory and detector

3.1 Results of a feasibility study in the central region of the Fréjus tunnels

The site located in the Fréjus mountain in the Alps, which is crossed by a road-tunnel connecting France (Modane) to Italy (Bardonecchia), has a number of interesting characteristics making it a very good candidate for the installation of a megaton-scale detector in Europe, aimed both at non-accelerator and accelerator based physics. Its great depth (4800 mwe, see figure 1), the good quality of the rock, the fact that it offers horizontal access, its distance from CERN (130 km), the opportunity of the excavation of a second ("safety") tunnel, the very easy access by train (TGV), by car (highways) and by plane (Geneva, Torino and Lyon airports), the strong support from the local authorities represent the most important of these characteristics.

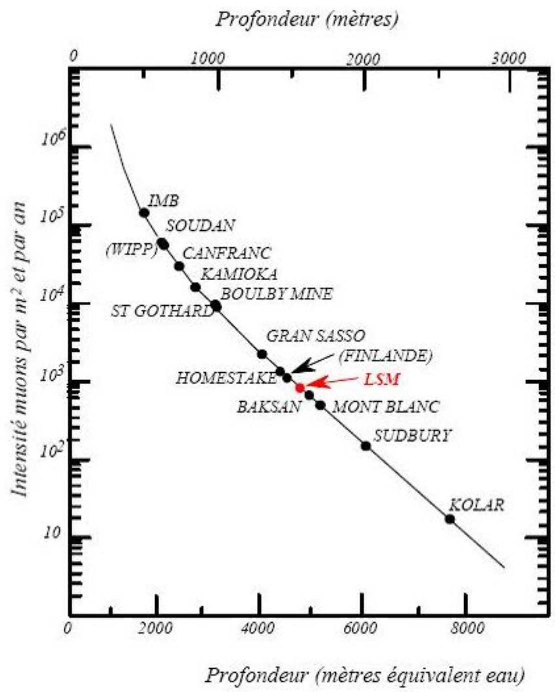


Figure 1: *Muon flux as a function of overburden. The Frejus site is indicated by "LSM".*

On the basis of these arguments, the DSM (CEA) and IN2P3 (CNRS) institutions decided to perform a feasibility study of a Large Underground Laboratory in the central region of the Fréjus tunnel, near the already existing, but much smaller, LSM Laboratory. This preliminary study has been performed by the SETEC (French) and STONE (Italian) companies and is now completed. These companies already made the study and managed the realisation of the Fréjus road tunnel and of the LSM (Laboratoire Souterain de Modane) Laboratory. A large number of precise and systematic measurements of the rock characteristics, performed at that time, have been used to make a pre-selection of the most favourable regions along the road tunnel and to constrain the simulations of the present pre-study for the Large Laboratory.

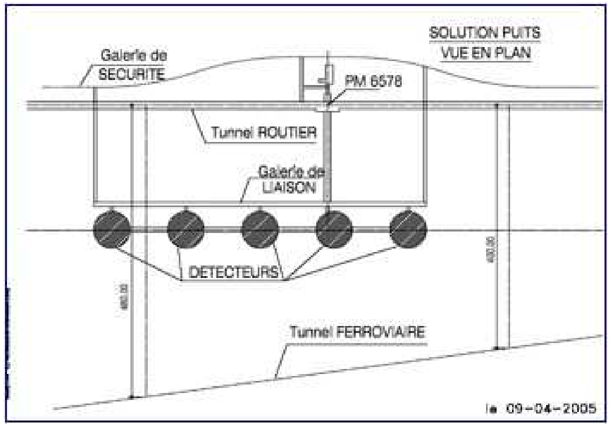


Figure 2: *Possible layout of the Fréjus underground laboratory.*

Three regions have been pre-selected : the central region and two other regions at about 3 km from each entrance of the tunnel. Two different shapes have been considered for the cavities to be excavated: the “tunnel shape” and the cylindrical “shaft shape”. The main purpose was to determine the maximum possible size for each of them, the most sensitive dimension being the width (the so-called “span”) of the cavities.

The very interesting results of this preliminary study can be summarized as follows :

1. the best site (rock quality) is found in the middle of the mountain, at a depth of 4800 mwe;
2. of the two considered shapes : “tunnel” and “shaft”, the “shaft shape” is strongly preferred;
3. cylindrical shafts are feasible up to a diameter $\Phi = 65$ m and a full height h = 80 m (~ 250000 m^3);
4. with “egg shape” or “intermediate shape between cylinder and egg shapes” the volume of the shafts could be still increased (see Fig. 3);
5. the estimated cost is $\sim$ 80 M Euro per shaft.

Fig. 2 shows a possible configuration for this large Laboratory, where up to five shafts, of about 250000 m^3 each, can be located between the road tunnel and the railway tunnel, in the central region of the Fréjus mountain.

Two possible scenarios for Water Čerenkov detectors are, for instance:

- 3 shafts of 250000 m^3 each, with a fiducial mass of 440 kton (“UNO-like” scenario).
- 4 shafts of 250000 m^3 each, with a fiducial mass of 580 kton.

In both scenarios one additional shaft could be excavated for a Liquid Argon and/or a liquid scintillator detector of about 100 kton total mass.

The next step will be a Design Study for this Large Laboratory, performed in close connection with the Design Study of the detectors and considering the excavation of 3 to 5 “shafts” of about 250 000 m^3 each, the associated equipments and the mechanics of the detector modules.

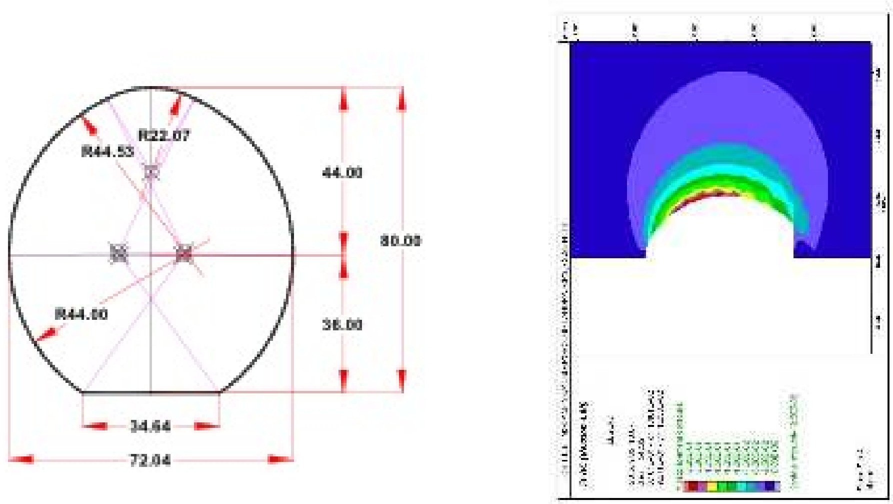


Figure 3: *An example of "egg shape" simulation, constrained by the rock parameter measurements made during the road tunnel and the present laboratory excavation. The main feasibility criterium is that the significantly perturbated region around the cavity should not exceed a thickness of about 10 m.*

3.2 Detector: general considerations

The 20 year long successful operation of the Super-Kamiokande detector has clearly demonstrated the capabilities and limitations of large water Čerenkov detectors:

- This technique is by far the cheapest and the most stable to instrument a very large detector mass, as price is dominated by the photodetectors and their associated electronics (this price growing like the outer surface of the detector), while the active mass, made of water, is essentially free except for the purification system
- These detectors are mainly limited in size by the finite attenuation length of Čerenkov light, found to be 80 meters at $\lambda = 400$ nm in Super-Kamiokande, and by the pressure of water on the photomultipliers at the bottom of the tank, which gives a practical limit of 80 m in height. At large depths, the maximal size of underground cavities actually limits relevant dimensions to about 70 m.
- The detection principle consists in measuring Čerenkov rings produced by charged particles going faster than light in water. This has several consequences:
    1. neutral particles and charged particles below Čerenkov threshold are undetectable, so that some energy may be missing
    2. complicated topologies are difficult to handle, and in practice only events with less than 3 to 5 rings are efficiently reconstructed
    3. ring topology, based on their degree of fuzziness, allows to separate between electromagnetic (e, γ) rings and (μ, π) rings

4. the threshold in particle energy depends mainly on photocathode coverage and also on water purity (due to radioactive backgrounds, such as radon). Super-Kamiokande has achieved an energy threshold of 5 MeV with 40% cathode coverage

5. due to points 1 and 2, water Čerenkov detectors are not suited to measure high energy neutrino interactions, as more rings and more undetectable particles are produced. A further limitation comes from the confusion between single electron or gamma rings and high energy π^0's giving 2 overlapping rings. In practice water Čerenkov's stay excellent neutrino detectors for energies below 1 (maybe 2) GeV, when interactions are mostly quasi-elastic and the 2 rings from π^0 well separated.

3.3 Detector design

Three detector designs are being carried out worldwide, namely Hyper-Kamiokande [7] in Japan, UNO [8] in the USA and the present project MEMPHYS in Europe. All of them are rather mild extrapolations of Super-Kamiokande, and rely on the expertise acquired after 20 years of operation of this detector. Their main characteristics are summarized in table 1.

These 3 projects aim at a fiducial mass around half a megaton, taking into account the necessity to have a veto volume on the edge of the detector, 1 to 2 meters thick, plus a minimal distance of about 2 meters between photodetectors and interaction vertices, leaving some space for ring development. The main differences between the 3 projects lie in the geometry of the cavities (tunnel shape for Hyper-Kamiokande, shafts for MEMPHYS, intermediate with 3 cubic modules for UNO), and the photocathode coverage, similar to Super-Kamiokande for Hyper-Kamiokande and MEMPHYS, while UNO keeps this coverage on only 1 cubic detector, while the 2 others have only 10% coverage for cost reasons. Another important parameter is the rock overburden, similar for UNO and MEMPHYS (4800 mwe), but smaller for Hyper-Kamiokande (1500 mwe), which might be a limiting factor for low energy physics, due to spallation products and fast neutrons produced by cosmic muons, more abundant by 2 orders of magnitude (see figure 1).

The basic unit for MEMPHYS consists of a cylindrical detector module 65 meters in diameter and 65 meters high, which can be housed in a cylindrical cavity with 70 meter diameter and 80 meter height, as proven by the prestudy. This corresponds to a water mass of 215 kilotons, that is only 4 times the Super-Kamiokande detector. Conservatively substracting 2 m for the outer veto plus 2 m for the fiducial volume, this leaves us with a fiducial mass of 146 kilotons per module. The baseline design uses 3 modules, giving a total fiducial mass of 440 kilotons, like UNO, corresponding to factor 20 increase over Super-Kamiokande (4 modules would give 580 kiloton fiducial mass). The modular aspect is actually mandatory for maintenance reasons, so that at least 2 of the 3 modules would be active at any time, giving 100% duty cycle for supernova explosions. Furthermore, it would offer the possibility to add Gadolinium in one of the modules, which has been advocated to improve diffuse supernova neutrino detection. We estimate an overall construction time of less than 10 years, and of course the first module could start physics during the completion of the two other modules.

Parameters	**UNO** (USA)	**HyperK** (Japan)	**MEMPHYS** (Europe)
Underground laboratory			
location	Henderson / Homestake	Tochibora	Fréjus
depth (m.e.w.)	4500/4800	1500	4800
Long Base Line (km)	$1480 \div 2760$ / $1280 \div 2530$	290	130
	FermiLab$\div$BNL	JAERI	CERN
Detector dimensions			
type	3 cubic compartments	2 twin tunnels	$3 \div 5$ shafts
		5 compartments	
dimensions	$3 \times (60 \times 60 \times 60)\text{m}^3$	$2 \times 5 \times (\phi = 43\text{m} \times L = 50\text{m})$	$(3 \div 5) \times (\phi = 65\text{m} \times H = 65\text{m})$
fiducial mass (kt)	440	550	$440 \div 730$
Photodetectors			
type	20" PMT	13" H(A)PD	12" PMT
number (internal detector)	57,000	20,000 per compartment	81,000 per shaft
surface coverage	40% (1/3) & 10% (2/3)	40%	30%

Table 1: *Some basic parameters of the three Water Čerenkov detector baseline designs*

3.4 Photodetection

The baseline photodetector choice is photomultipliers (PMT) as they have successfuly equipped the previous generation of large water Čerenkov detectors and many other types of presently running detectors in HEP. The PMT density should be chosen to allow excellent sensitivity to a broad range of nucleon decays and neutrino physics while keeping the instrumentation costs under control.

Our goal for MEMPHYS is to reach in the whole detector the same energy threshold as Super-Kamiokande, that is 5 MeV, important for solar neutrino studies, for the proton decay into $K^+\nu$ using the 6 MeV tag from ^{15}N desexcitation, and also very useful for SN explosions, since the measurement of the ν_μ and ν_τ fluxes could be achieved using the neutral current excitation of Oxygen.

Our first approach was to consider 20" Hamamatsu tubes as used by Super-Kamiokande, but the cost for 40% coverage becomes prohibitive, as these tubes are manually blown by specially trained people, which makes them very expensive. Following a suggestion presented at the NNN05 conference by Photonis company, we have considered the possibility of using instead 12" PMT's, which can be automatically manufactured and have better characteristics compared to 20" tubes: quantum efficiency (24% vs 20%), collection efficiency (70% vs 60%), risetime (5 ns vs 10 ns), jitter (2.4 ns vs 5.5 ns). Based on these numbers, 30% coverage with 12" PMT's would give the same number of photoelectrons per MeV as a 40% coverage with 20" tubes. Taking into account the ratio of photocathodes (615 cm^2 vs 1660 cm^2), this implies that going from 20" tubes to twice as many 12" tubes will give the same detected light, with a bonus on time resolution and on pixel locations, so that MEMPHYS performances should be at least as good as Super-Kamiokande. A GEANT4 based Monte Carlo is under development to quantify the effective gain. Pricewise, each 20" PMT costing 2500 Euros is replaced by 2 12" PMT's costing 800 Euros each. The only caveat is to make sure that the savings on PMT's are not cancelled by the doubling of electronic channels. An R&D on electronics integration is presently underway (see Sec. 3.6).

3.5 Photomultiplier tests

A joint R&D program between Photonis company and French laboratories has been launched to test the quality of the 12" PMTs in the foreseen conditions of deep water depth, and to make a realistic market model for the production of about 250,000 PMTs that would be necessary to get the 30% geometrical coverage.

In parallel, studies on new photo-sensors have been launched. The aim is to reduce cost, while improving production rate and performance, as it is essential to achieve the long term stability and reliability which is proven for PMTs. Hybrid photosensors (HPD) could be a solution: the principle has been proven by ICRR and Hamamatsu with a 5" HPD prototype. Successful results from tests of an 13" prototype operated with 12 kV are now available, showing a $3 \cdot 10^4$ gain, good single photon sensitivity, 0.8 ns time resolution and a satisfactory gain and timing uniformity over the photo-cathode area. The development of HPD has also been initiated in Europe, in collaboration with Photonis.

3.6 Smart-photodetector electronics

The coverage of large areas (around 17,500 m^2 for MEMPHYS) with photodetectors at lowest cost implies a readout integrated electronics circuit (called ASIC). This makes it possible to integrate: high-speed discriminator on the single photoelectron (pe), a trigger coincidence logics to strongly reduce the counting rate due to the noise, the digitisation of the charge on 12 bits ADC to provide numerical signals on a large dynamical range (200 pe), the digitisation of time on 12 bits TDC to provide time information with a precision of 1 ns, and channel-to-channel gain adjustment to homogenize the response of the photomultipliers and to thus use a common high voltage. Such an ASIC for readout electronics allows moreover a strong reduction of the costs, as well as external components (high-voltage units, cables of great quality...) since the electronics and the High Voltage may be put as close as possible to the PMTs and the generated numerical signals are directly usable by the data acquisition computers (Fig. 4).

The main difficulty in associating very fast analog electronics and digitization on a broad dynamic range does not make it possible yet to integrate all these functions in only one integrated circuit, but certain parts were already developed separately as for example in the OPERA Read Out Channel [9] (Fig. 5). The evolution of integrated technologies, in particular BiCMOS SiGe 0.35μm, now make it possible to consider such circuits and has triggered a new campaign of research and development.

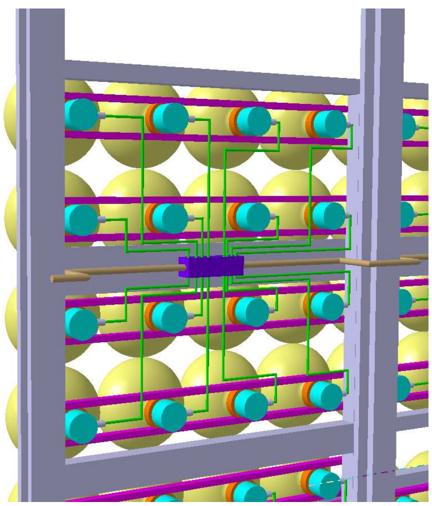


Figure 4: *Sketch of a possible photosensor basic module composed of a matrix of* 4×4 *12" PMTs with the electronic box containing the High Voltage unit and the Readout chip.*

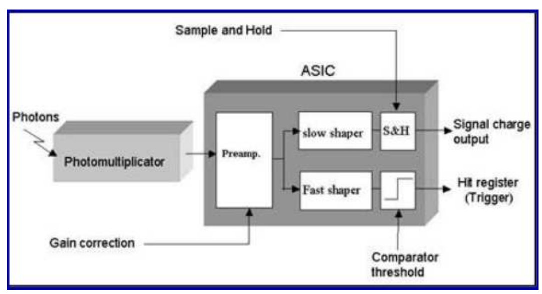


Figure 5: *Sketch of the existing Read Out electronics developed for the OPERA Target Tracker and that is intented to be extended for MEMPHYS by integrating the ADC and TDC.*

4 Detector Performance

As mentioned above, we consider a massive water Čerenkov detector à la UNO [7] and review the performances of such a detector for the main physics fields.

4.1 Proton decay sensitivity

For proton decay, no specific simulation for MEMPHYS has been carried out yet. We therefore rely on the study done by UNO, adapting the results to MEMPHYS (which has an overall better coverage) when possible.

4.1.1 $p \to e^+\pi^0$

Following UNO study, the detection efficiency of $p \to e^+\pi^0$ (3 showering rings event) is ϵ =43% for a 20 inch-PMT coverage of 40% or its equivalent, as envisioned for MEMPHYS. The corresponding estimated atmospheric neutrino induced background is at the level of 2.25 events/Mt.yr. From these efficiencies and background levels, proton decay sensitivity as a function of detector exposure can be estimated (see Fig. 6).

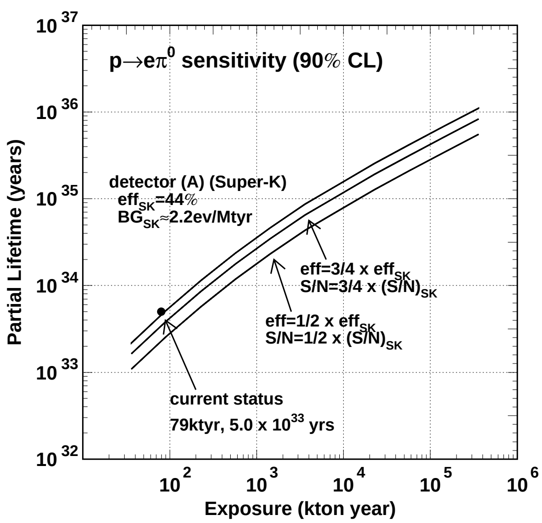


Figure 6: *Sensitivity for $e^+\pi^0$ proton decay lifetime, as determined by UNO [7]. MEMPHYS corresponds to case (A).*

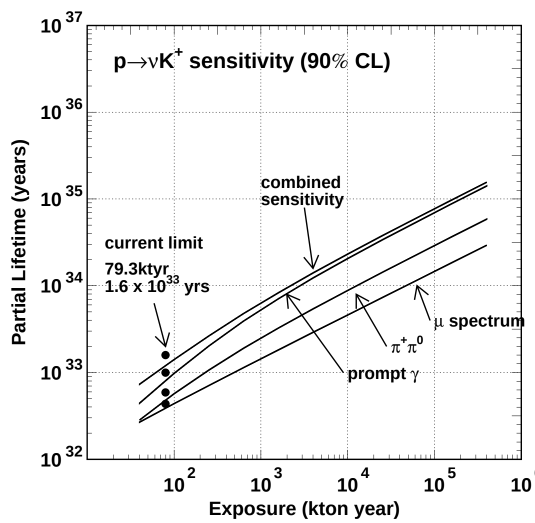


Figure 7: *Expected sensitivity on νK^+ proton decay as a function of MEMPHYS exposure [7] (see text for details).*

10^{35} years partial lifetime could be reached at the 90% CL for a 5 Mt.yr exposure with MEMPHYS (similar to case A in figure 6).

4.1.2 $p \to \overline{\nu} K^+$

Since the K^+ is below the Čerenkov threshold, this channel is detected via the decay products of the kaon: a 256 MeV/c muon and its decay electron (type I) or a 205 MeV/c π^+ and π^0 (type II), with the possibility of a delayed (12 ns) coincidence with the 6 MeV

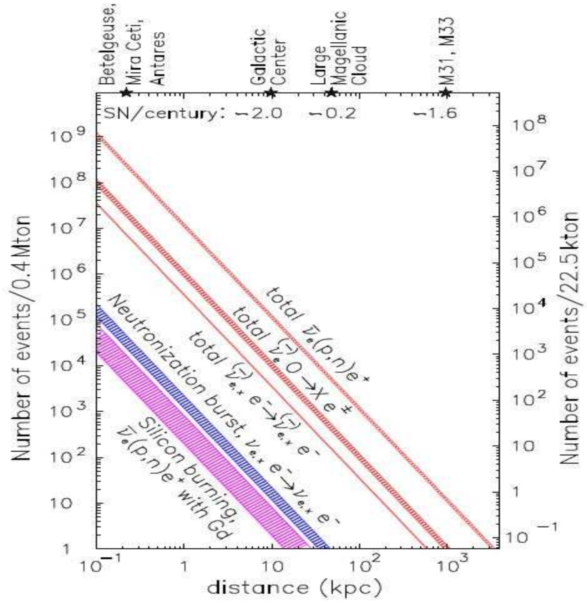


Figure 8: *The number of events in a 400 kt water Čerenkov detector (left scale) and in SK (right scale) in all channels and in the individual detection channels as a function of distance for a supernova explosion [10].*

nuclear de-excitation prompt γ (Type III). In Super-Kamiokande, the efficiency for the reconstruction of $p \to \overline{\nu} K^+$ is $\epsilon = 33\%$ (I), 6.8% (II) and 8.8% (III), and the background is at the 2100, 22 and 6/Mt.yr level. For the prompt γ method, the background is dominated by mis-reconstruction. As stated by UNO, there are good reasons to believe that this background can be lowered at the level of 1/Mt.yr corresponding to the atmospheric neutrino interaction $\nu p \to \nu \Lambda K^+$. In these conditions, and using Super-Kamiokande performances, a 5 Mt.yr MEMPHYS exposure would allow to reach the 2×10^{34} years partial lifetime (see Fig. 7).

4.2 Supernova neutrinos

4.2.1 Core-collapse

The large mass of a MEMPHYS-type detector means that the sample of events collected during a supernova explosion would outnumber that of all other existing detectors. For instance, for a supernova at 10 kpc $\sim 2 \times 10^5$ events would be observed, whereas Super-Kamiokande (22.5 kt) will see only 9,000 events (see Figure 8, from ref. [10]). These numbers are to be compared with the 19 (11 for Kamiokande and 8 for IMB) events coming from the SN1987A in the Large Magellanic Cloud (50 kpc).

An estimated number of 3 ± 1 supernovae occur in our galaxy and its satellites every century. A MEMPHYS-type detector would also be sensitive to supernovae occurring throughout the local group of galaxies. For a supernova explosion in Andromeda (730-890 kpc), the proposed detector will collect roughly the same amount of neutrinos detected for the SN1987A. A handful of events might be seen even at a distance as large as 3 Mpc.

One of the unsolved problems in astrophysics is the mechanism of supernova core-collapse. Inverse beta decay events from the silicon burning phase preceding the supernova explosion have very low (sub-threshold) positron energies, and could only be detected through neutron capture by adding Gadolinium [4], provided that they can be statistically distinguished from background fluctuations. The silicon burning signal should then be seen with a statistical significance of 2÷8 standard deviations at a reference distance of 1 kpc. Unfortunately, at the galactic center (∼10 kpc) the estimated silicon burning signal would be 100 times smaller and thus unobservable.

There are better prospects to observe the neutronization burst from a galactic supernova by means of elastic scattering on electrons, including contributions from all flavors: a 0.4 Mton detector might observe such signal with a statistical significance at the level of 4 standard deviations. At the distance of the Large Magellanic Cloud, however, the sensitivity drops dramatically.

Returning to the overall rate in the inverse beta channel, the high statistics available for a galactic supernova explosion will allow many possible spectral analyses, providing insight both on the properties of the collapse mechanism and on those of neutrinos.

For the first topic, an example is given in [10] in the context of shock-wave effects, based on the comparison of arrival times in different energy bins.

Concerning the spectral properties which depend on neutrino oscillation parameters, it has been shown in [11] that a detector like the proposed one, considering the inverse-beta channel alone with the current best values of solar neutrino oscillation parameters, would allow the determination of the parameter τ_E, defined as the ratio of the average energy of time-integrated neutrino spectra $\tau_E = \langle E_{\bar{\nu}_\mu} \rangle / \langle E_{\bar{\nu}_e} \rangle$, with a precision at the level of few percent, to be compared with a ∼20% error possible at Super-Kamiokande. This would make it possible to distinguish normal from inverted mass hierarchy, if $\sin^2\theta_{13} > 10^{-3}$ [12]. In the region $\sin^2\theta_{13} \sim (3\cdot 10^{-6} - 3\cdot 10^{-4})$, measurements of $\sin^2\theta_{13}$ are possible with a sensitivity at least an order of magnitude better than planned terrestrial experiments [12].

Up to now we have investigate supernova explosions occurring in our galaxy, however the calculated rate of supernova explosions within a distance of 10 Mpc is about one per year. Although the number of events from a single explosion at such large distances would be small, the signal could be separated from the background with the request to observe at least two events within a time window comparable to the neutrino emission time-scale (∼10 sec), together with the full energy and time distribution of the events [13]. In a MEMPHYS-type detector, with at least two neutrinos observed, a supernova could be identified without optical confirmation, so that the start of the light curve could be forecasted by a few hours, along with a short list of probable host galaxies. This would also allow the detection of supernovae which are either heavily obscured by dust or are optically dark due to prompt black hole formation. Neutrino detection with a time coincidence could therefore act as a precise time trigger for other supernova detectors (gravitational antennas or neutrino telescopes).

Finally, one can notice that electron elastic scattering events would provide a pointing accuracy on the supernova explosion of about 1°.

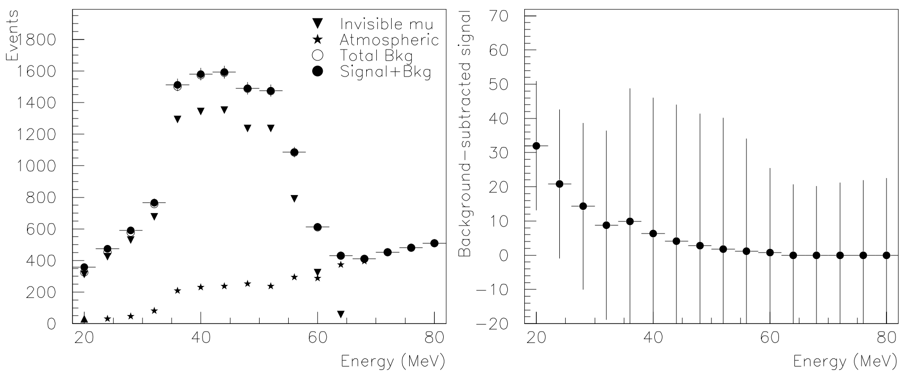


Figure 9: *Diffuse Supernova Neutrino signal and backgrounds (left) and subtracted signal with statistical errors (right) in a 440 kt water Čerenkov detector with a 10 years exposure. The selection efficiencies of SK were assumed; the efficiency change at 34 MeV is due to the spallation cut.*

4.2.2 Diffuse Supernova Neutrinos

An upper limit on the flux of neutrinos coming from all past core-collapse supernovae (the Diffuse Supernova Neutrinos, [1], DSN) has been set by the Super-Kamiokande experiment [14], however most of the estimates are below this limit and therefore DSN detection thorough inverse beta decay appears to be feasible at a megaton-scale water Čerenkov detector.

Typical estimates for DSN fluxes (see for example [15]) predict an event rate of the order of $0.1 \div 0.5\ \mathrm{cm^{-2}s^{-1}MeV^{-1}}$ for energies above 20 MeV, a cut imposed by the rejection of spallation events. After experimental selections analogous to the ones applied in the Super-Kamiokande analysis, such events are retained with an efficiency of about 47% for energies between 20 and 35 MeV; this is to be considered as a very conservative estimate at MEMPHYS, where the bigger overburden will reduce the cosmic-muon induced background and less stringent selection criteria can be applied. Two irreducible backgrounds remain: atmospheric ν_e and $\bar{\nu}_e$, and decay electrons from the so called "invisible muons" generated by CC interaction of atmospheric neutrinos and having an energy below threshold for Čerenkov signal.

The spectra of the two backgrounds were taken from the Super-Kamiokande estimates and rescaled to a fiducial mass of 440 kton of water, while the expected signal was computed according to the model called LL in [15]. The results are shown in Fig. 9: the signal could be observed with a statistical significance of about 2 standard deviations after 10 years.

As pointed out in [10], with addition of Gadolinium [4] the detection of the captured neutron would give the possibility to reject neutrinos other than $\bar{\nu}_e$ from spallation events

[1] We prefer to denote these neutrinos as "Diffuse" rahter than "Relic" to avoid confusion with the primordial neutrinos produced one second after the Big Bang.

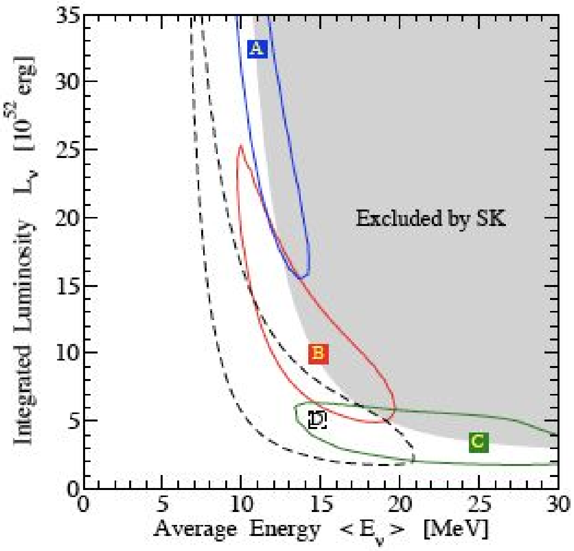


Figure 10: *Possible 90% C.L. measurement of the emission parameters of supranova $\bar{\nu}_e$ emission after 5 years running of a Gd-enhanced Super-Kamiokande detector, which would correspond to 1 year of one MEMPHYS shaft. The points corespond to different assumptions on the average energy and integrated luminaosty: A,B,C are taken at the edge of the region excluded by SK, D is often regarded aas the canonical values for $\bar{\nu}_e$ emission before neutrino mixing. See [16].*

and from atmospheric origin, and the detection threshold could be lowered significantly - to about 10 MeV - with a large gain on signal statistics. The tails of reactor neutrino spectra would become the most relevant source of uncertainty on the background. In such condition, not only would the statistical significance of the signal become much higher, but is would even be possible to distinguish between different theoretical predictions. For example, the three models considered in [15] would give 409, 303 and 172 events respectively above 10 MeV. An analysis of the expected DSN spectrum that would be observed with a Gadolinium-loaded water Čerenkov detector has been carried out in [16]: the possible limits on the emission parameters of supernova $\bar{\nu}_e$ emission have been computed for 5 years running of a Gd-enhanced SuperKamiokande detector, which would correspond to 1 year of one MEMPHYS shaft, and are shown in Fig. 10. Detailed studies on characterization of the backgrounds, however, are needed.

4.3 Neutrino oscillation physics

4.3.1 With the CERN-SPL SuperBeam

In the initial CERN-SPL SuperBeam project [17, 18, 19, 20, 21] the planned 4MW SPL (Superconducting Proton Linac) would deliver a 2.2 GeV/c proton beam sent on a Hg target to generate an intense π^+ (π^-) beam focused by a suitable magnetic horn in a short decay tunnel. As a result, an intense ν_μ beam is produced mainly via the π-decay,

$\pi^+ \rightarrow \nu_\mu\ \mu^+$ providing a flux $\phi \sim 3.6{\cdot}10^{11}\nu_\mu/\text{year}/\text{m}^2$ at 130 Km of distance, and an average energy of 0.27 GeV. The ν_e contamination from K is suppressed by threshold effects and amounts to 0.4%. The use of a near and far detector (the latter 130 km away at Fréjus [22], see Sec. 3.1) will allow for both ν_μ-disappearance and $\nu_\mu \rightarrow \nu_e$ appearance studies. The physics potential of the 2.2 GeV SPL SuperBeam (SPL-SB) with a water Čerenkov far detector with a fiducial mass of 440 kton, has been extensively studied [18].

New developments show that the potential of the SPL-SB potential could be improved by rising the SPL energy to 3.5 GeV [23], to produce more copious secondary mesons and to focus them more efficiently. This increase in energy is made possible by using state of the art RF cavities instead of the previously foreseen LEP cavities [24].

The focusing system (magnetic horns) originally optimized in the context of a Neutrino Factory [25, 26] has been redesigned considering the specific requirements of a Super Beam. The most important points are that the phase spaces that are covered by the two types of horns are different, and that for a Super Beam the pions to be focused should have an energy of the order of 800 MeV to get a mean neutrino energy of 300 MeV. The increase in kaon production rate, giving higher ν_e contamination, has been taken into account, and should be refined using HARP results [27].

In this upgraded configuration, the neutrino flux is increased by a factor ~ 3 with respect to the 2.2 GeV configuration, and the number of expected ν_μ charged currents is about 95 per kton $\cdot$ yr in MEMPHYS.

A sensitivity $\sin^2(2\theta_{13}) < 0.8 \cdot 10^{-3}$ is obtained in a 2 years ν_μ plus 8 year $\overline{\nu}_\mu$ run (for $\delta = 0$, intrinsic degeneracy accounted for, sign and octant degeneracies not accounted for), allowing for a discovery of CP violation (at 3 σ level) for $\delta \geq 60^\circ$ for $\sin^2(2\theta_{13}) = 1.8 \cdot 10^{-3}$ and improving to $\delta \geq 20^\circ$ for $\sin^2(2\theta_{13}) \geq 2 \cdot 10^{-2}$ [28, 29]. These performances are shown in Fig. 13, they are found equivalent to Hyper-Kamiokande. These limits have been obtained first using realistic simulations based on Super-Kamiokande performances (Background level, signal efficiencies, and associated systematics at the level of 2%), and more recently confirmed using GLoBES [30].

Let us conclude this section by mentioning that further studies of the SPL superbeam will take place inside the Technical Design Study to be submitted to Europe by the neutrino factory community towards the end of 2006.

4.3.2 With the CERN BetaBeams

BetaBeams have been proposed by P. Zucchelli in 2001 [31]. The idea is to generate pure, well collimated and intense ν_e ($\overline{\nu}_e$) beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring in 10 ns long bunches, to suppress the atmospheric neutrino backgrounds. The resulting BetaBeam spectra can be easily computed knowing the beta decay spectrum of the parent ion and the Lorentz boost factor γ, and these beams are virtually background free from other flavors. The best ion candidates so far are ^{18}Ne and ^{6}He; for ν_e and $\overline{\nu}_e$ respectively. The schematic layout of a Beta Beam is shown in figure 12. It consists of three parts:

1. A low energy part, where a small fraction (lower than 10%) of the protons accelerated by the SPL are shot on specific target to produce ^{18}Ne or ^{6}He; these ions are then collected by an ECR source of new generation [32] which delivers ion bunches with

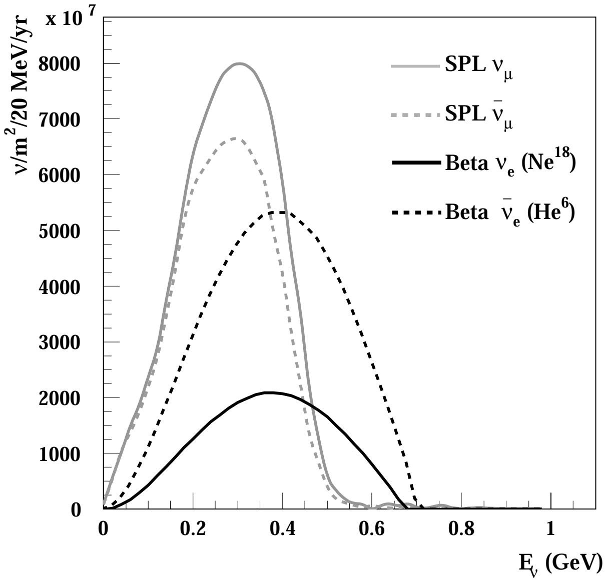


Figure 11: *Neutrino flux of β-Beam ($\gamma = 100$) and CERN-SPL SuperBeam, 3.5 GeV, at 130 Km of distance.*

100 keV energy, then accelerated in a LINAC up to 100 MeV/u. This part could be shared with nuclear physicists involved in the EURISOL project [33, 34].

2. The acceleration to the final energy uses a rapid cycling cyclotron (labelled PSB) which further accelerates and bunches the ions before sending them to the PS and the SPS, where they reach their final energy (γ around 100). In this process, 16 bunches (150 ns long) in the booster are transformed into 4 bunches (10 ns long) in the SPS.

3. Ions of the required energy are then stored in a decay ring, with 2500 m long straight sections for a total length of 7000 m, so that 36% of the decays give a strongly collimated and ultra pure neutrino beam aimed at the Fréjus detector.

A baseline study for the betabeam has been initiated at CERN, and is now going on within the european FP6 design study for EURISOL. A specific task is devoted to the study of the high energy part (last 2 items above). A complete conceptual design for the decay ring has already been performed. The injection in the ring uses the asymetric merging scheme, validated by experimental tests at CERN. The actual performances of the new ECR sources will also be studied with prototypes in the framework of the EURISOL design study.

The potential of such betabeams sent to MEMPHYS has been studied in the context of the baseline scenario, using reference fluxes of $5.8{\cdot}10^{18}$ ^{6}He useful decays/year and $2.2{\cdot}10^{18}$ ^{18}Ne decays/year, corresponding to a reasonable estimate by experts in the field of the ultimately achievable fluxes .

First oscillation physics studies [36, 37, 38, 39] used $\gamma_{^6\mathrm{He}} = 60$ and $\gamma_{^{18}\mathrm{Ne}} = 100$. But it was soon realized that the optimal values were actually $\gamma = 100$ for both species, and the corresponding performances are shown in figure 13, exhibiting a strong improvement

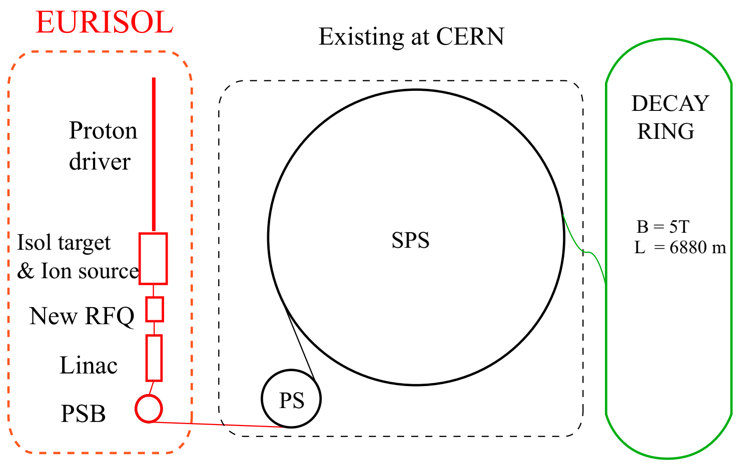


Figure 12: *A schematic layout of the BetaBeam complex. On the left, the low energy part is largely similar to the EURISOL project [33]. The central part (PS and SPS) uses existing facilities. On the right, the decay ring has to be built.*

over SPL superbeam performances, extending the range of sensitivity for $\sin^2(2\theta_{13})$ down to $2 \cdot 10^{-4}$ and improving CP violation sensitivity at lower values of θ_{13}.

To conclude this section, let us mention a very recent development of the Beta Beam concept leading to the possibility to have monochromatic, single flavor neutrino beams by using ions decaying through the electron capture process [40, 41]. A suitable ion candidate exists: ^{150}Dy, whose performances have been already delineated [40]. Such beams would in particular be perfect to precisely measure neutrino cross sections in a near detector with the possibility of an energy scan by varying the γ value of the ions.

For a review of the different Beta Beam configurations, see [42].

4.3.3 Combining SPL Super Beam and Beta Beam

Since betabeams use only a small fraction of the protons available from the SPL, both beta beam and superbeam can be run at the same time. The combination of superbeam and betabeam results further improves the sensitivity on θ_{13} and δ, as shown on figure 13. It is better in all cases than Hyper-Kamiokande sensitivity, except maybe for very large values of $\sin^2(2\theta_{13})$ above 0.04 The sensitivity on CP violation is even better than that of a neutrino factory for $\sin^2(2\theta_{13})$ above $3.5 \cdot 10^{-3}$ (but neutrino factories are still a factor 3 better for θ_{13} sensitivity). This combination of super and betabeams offers other advantages, since the same parameters θ_{13} and δ_{CP} may be measured in many different ways, using 2 pairs of CP related channels, 2 pairs of T related channels, and 2 pairs of CPT related channels which should all give coherent results. In this way the estimates of the systematic errors, different for each beam, will be experimentally cross-checked. And, needless to say, the unoscillated data for a given beam will give a large sample of events corresponding to the small searched-for signal with the other beam, adding more handles on the understanding of the detector response.

The MEMPHYS detector performances in conjunction with the SPL SuperBeam and the $\gamma = 100$ Beta Beam have been recently revised in [43]. In this paper are also computed

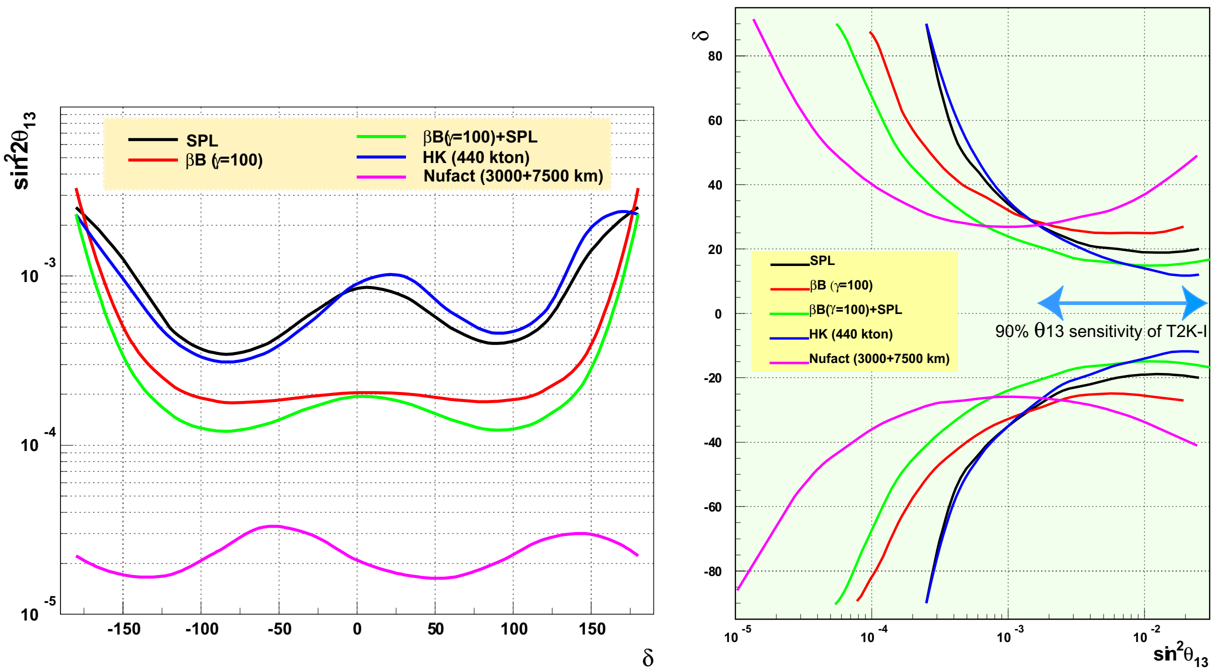


Figure 13: *LEFT:* θ_{13} *90% C.L. sensitivity as function of* δ_{CP} *for* $\Delta m^2_{23} = 2.5{\cdot}10^{-3} eV^2$, $\mathrm{sign}(\Delta m^2_{23}) = 1$, *2% systematic errors. SPL-SB sensitivities have been computed for a 2 year* ν_μ *+ 8 year* $\overline{\nu}_\mu$ *run,* βB *(*$\gamma = 100$*) for a 5 year* ν_e *+ 5 year* $\overline{\nu}_e$ *run, 200 MeV energy bins for both beams. The combination of SPL-SB and* βB *is also shown. HK and NuFACT curves are adapted from [35]: HK curves corresponds to Hyper-Kamiokande with the same fiducial mass, running time and systematics as MEMPHYS, using the 4MW beam from JAERI. The NuFACT curve corresponds to 5 year runs for each polarity, two 50kton iron detectors located at 3000 and 7000 km receiving neutrinos from* 10^{21} *useful 50 GeV muon decays per year, detector systematics set at 2%, matter profile uncertainty set at 5%, energy threshold set at 4 GeV. RIGHT:* δ_{CP} *discovery potential at* 3σ *computed for the same conditions.*

the experimental capabilities of measuring sign(Δm^2_{23}) and the θ_{23} octant by combining atmospheric neutrinos, detected with large statistics in a megaton scale water Čerenkov detector, with neutrino beams; as initially pointed out in [44]. Following these studies, the MEMPHYS detector could unambiguously measure all the today unknown neutrino oscillation parameters. It's worth to stress the fact that the short baseline allows to measure leptonic CP violation without any subtraction of the fake CP signals induced by matter effects, still having a sizable sensitivity on the mass hyerarchy determination thanks to the atmospheric neutrinos.

4.3.4 Comparison with other projects

Before the advent of megaton class detectors receiving neutrino from a Super Beam and/or Beta Beam, several beam experiments (MINOS, OPERA, T2K, NoVA) and reactor experiments (such as Double-CHOOZ) will have improved our knowledge on θ_{13}.
If θ_{13} is found by these experiments, it will be "big" ($\sin^2(2\theta_{13}) > 0.02$) and megaton detectors will be the perfect tool to study CP violation, with no need for a neutrino factory. If on the contrary, only an upper limit around $5 \cdot 10^{-3}$ to 10^{-2} is given on $\sin^2(2\theta_{13})$, one might consider an alternative between a staged strategy, starting with megaton detectors, to explore $\sin^2(\theta_{13})$ down to $3 \cdot 10^{-4}$ and start a rich program of non oscillation physics, eventually followed by a neutrino factory if θ_{13} is not found; or a more aggressive strategy, aiming directly at neutrino factories to explore $\sin^2(2\theta_{13})$ down to 10^{-4} but with no guarantee of success; in the latter case, the non-oscillation physics (proton decay, sypernovae) is lost, but would be replaced by precision muon physics (which has to be assessed and compared with other projects in this field).
There is no doubt that a neutrino factory has a bigger potential than megaton detectors for very low values of θ_{13} (below $5 \cdot 10^{-3}$), and the only competition in that case could come from so-called high energy beta-beams. An abundant litterature has been published on this subject (see [44, 45, 46, 47, 48, 49]), but most authors have taken as granted that the neutrino fluxes from betabeams could be kept the same at higher energies, which is far from evident [50] and implies a lot of R&D on the required accelerators and storage rings before a useful comparison can be made with neutrino factories.

Presently, the only pertinent comparison is between the several megaton projects, namely UNO, Hyperkamiokande and MEMPHYS, or their variants using liquid argon technology (such as FLARE in the USA, GLACIER in Europe). In this document, we have shown a comparison between Hyperkamiokande and MEMPHYS, showing a definite advantage for the latter, due to the betabeam. However, recent variants of Hyperkamiokande using a second detector in Korea would have to be considered. UNO, for the time being, refers to a study of a very long baseline (2500 km) neutrino wide band superbeam produced at Brookhaven, which gives a disappointing sensitivity on θ_{13} at the level of 0.02 (this is due to the fact that this multiGeV beam leads to high π^0 backgrounds in a water Čerenkov detector, as explained before).
Liquid argon detector performances have to be studied, but they will probably suffer from their lower mass for the lower limit on θ_{13}, while a better visibility of event topologies would probably help for high values of θ_{13}, when statistics become important and systematics dominate; all this has still to be carefully quantified.

Let us mention that a unified way to compare different projects has been made available to the community , this is the GLoBES package [30]. Figure 13 in this document was actually produced using GLoBES, and some of us are actively pursuing GLoBES-based comparisons in the framework of the International Scoping Study (ISS), with results expected by mid-2006. They will also address the best way to solve problems related to the degeneracies on parameter estimates due to the sign of Δm^2_{23}, the quadrant ambiguity on θ_{23}, as well as intrinsic (analytic) ambiguities (In the present document, we have supposed θ_{23} equal to 45°, and the absence of matter effects at low energies make the results insensitive to the mass hierarchy). But the main point is to feed GLoBES with realistic estimates of the expected performances of the different projects, in terms of background rejection, signal efficiencies and the various related systematic uncertainties. A coordinated effort to get realistic numbers for the different projects will be, if successful, an important achievement of the ISS initiative.

4.4 Solar neutrinos

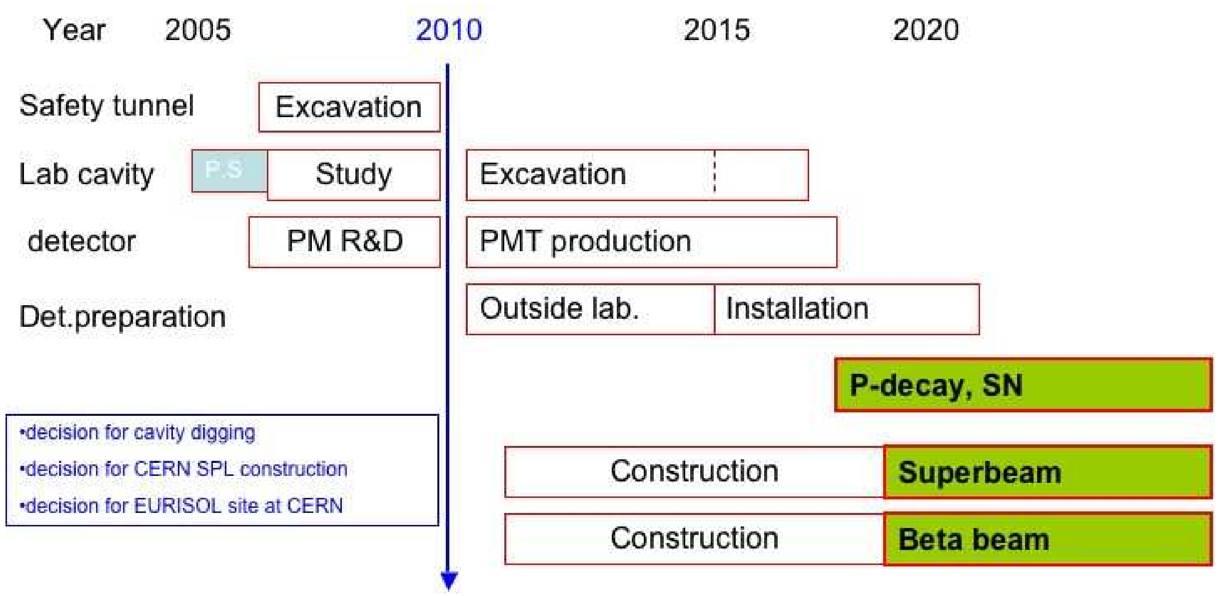
Water Čherenkov detectors have measured the high energy tail of the solar ^{8}B neutrino flux using electron-neutrino elastic scattering [51]. Since such detectors could record the time of an interaction and reconstruct the energy and direction of the recoiling electron, unique information of the spectrum and time variation of the solar neutrino flux was extracted. This provided further insights into the "solar neutrino problem", the deficit of the neutrino flux (measured by several experiments) with respect to the flux expected by the standard solar models . It also constrained the neutrino flavor oscillation solutions in a fairly model-independent way.

The recoiling electrons from solar neutrino interactions are low in energy and produce few Čherenkov photons. However, if at least 20 % of the detection surface is photosensitive then solar neutrinos above 10 MeV could be detected even with a modest photosensor efficiency. A detector with larger size than any existing Water Čerenkov has the potential to measure spectrum and time-variation of the high-energy solar neutrino flux more precisely, if systematic uncertainties can be kept small. For example, Super-Kamiokande's measurements obtained from 1258 days of data could be repeated in about half a year (the seasonal flux variation measurement requires of course a full year). In particular, a first measurement of the flux of the rare hep neutrinos may be possible. Elastic neutrino-electron scattering is strongly forward peaked. To separate the solar neutrino signal from background events, this directional correlation is exploited. Angular resolution is limited by multiple scattering. The reconstruction algorithm first reconstructs the vertex from the PMT times and then the direction assuming a single Cherenkov cone originating from the reconstructed vertex. Reconstructing 7 MeV events in a 400 kton fiducial volume water Čerenkov (UNO,MEMPHYS,...) seems not to be a problem.

This means we are able to make improvements in solar neutrino detection with a megaton-scale Čerenkov detector: even if it is not the main goal of such a detector it could be an excellent by-product.

5 Schedule

The following table presents an optimal schedule for the European project taking into account the key date of the completion of the new tunnel excavation around 2010. Soon after, CERN will have to decide its post-LHC strategy, while nuclear physicists will hopefully choose CERN as the host laboratory for the EURISOL project. We would also like to stress that the schedule of the neutrino beams from CERN is not constraining the start of the other non accelerator items of research.



6 Conclusions

In conclusion a megaton scale Water Čerenkov detector at the Frejus site will address a series of fundamental issues :

- explore the nucleon decay with a sensitivity an order of magnitude better than current limits on different channels
- in the case of a galactic or near galactic supernova explosion, track the explosion in unprecedented detail providing at the same time information on the third oscillation angle beyond what is currently achievable in terrestrial experiments
- provide a trigger for supernova explosions for other astroparticle detectors for supernova exploding in a range of up to 3 Mpc, knowing that 1 supernova explosion per year is expected within a distance of 10 Mpc
- provide a 4 sigma detection of diffuse supernova neutrinos after 2-3 years of operation
- in association with a superbeam and betabeam from CERN obtain a sensitivity to the third oscillation angle down to $\sin^2(2\theta_{13}) \sim 10^{-4}$ and detect maximal CP violation at 3 sigmas for $\sin^2(2\theta_{13})$ larger than $3 \cdot 10^{-4}$

A series of other physics topics, not mentioned here, will also be adressed: for instance neutrino physics, as well as interdisciplinary topics in rock mechanics, geobiology, geochemistry, geohydrology, geomechanics and geophysics that could benefit from a large scale underground excavation.

We believe that our project compares favorably with other similar projects around the world, and should be seriously considered as a very attractive major european project after the LHC. The proposed strategy is thus the following: a megaton-scale detector could be installed at Fréjus and start physics in 2018. It would start proton decay and supernova searches, which would last several decades. As soon as the neutrino beam from SPL is available, neutrino oscillation studies can start, and the advent of a beta beam would increase significantly the performances of the detector.

The signatories are eager to see the MEMPHYS project come to life. They are aware that the actual location of a megaton detector will depend on many issues, in particular the share of future big equipments (such as linear colliders) worldwide. They are prepared to do the proposed physics in any country, and have already set up collaborations with their japanese and american colleagues. An inter-regional yearly (US-Europe-Japan) workshop series NNN-XX (Next generation of Nucleon decay and Neutrino Physics detectors) organizes and structures this convergence of interests. The authors of this document hope however that Europe will not miss a unique opportunity to keep a leading role in the underground physics, complementary to the Gran Sasso.

Furthermore, it is obvious that the current proposal is complementary to other proposals for large undergrounds detectors using liquid scintillator (LENA) or liquid argon technologies (GLACIER) in order to pursue the same physics goals. The advantage of the water Čerenkov technique lies on the possibility to instrument very large masses, while liquid argon detectors can have an excellent resolution and liquid scintillators very low detection thresholds for neutrino physics. On the technology side the water Čerenkov seems a straightforward extension of the existing techniques while for instance the liquid argon option presents daring technological challenges. The realisation of the complementarities in physics potential and the common R&D issues (large underground caverns and containers: excavation issues and safety, large area low cost photodetection and electronics, purification and background issues, interdisciplinary issues, etc.) prompted the proponents of the above solutions to start federating their efforts in order to exploit the possible synergies in view of common future proposals to the European Union [52] and elsewhere.

7 Acknowledgements

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