Large underground, liquid based detectors for astro-particle physics in Europe: scientific case and prospects

D Autiero [1], J Äystö [2], A Badertscher [3], L Bezrukov [4], J Bouchez [5], A Bueno [6], J Busto [7], J-E Campagne [8], Ch Cavata [9], L Chaussard [1], A de Bellefon [10], Y Déclais [1], J Dumarchez [11], J Ebert [12], T Enqvist [13], A Ereditato [14], F von Feilitzsch [15], P Fileviez Perez [16], M Göger-Neff [17], S Gninenko [4], W Gruber [3], C Hagner [12], M Hess [14], K A Hochmuth [17], J Kisiel [18], L Knecht [3], I Kreslo [14], V A Kudryavtsev [19], P Kuusiniemi [13], T Lachenmaier [15], M Laffranchi [3], B Lefievre [10], P K Lightfoot [19], M Lindner [20], J Maalampi [2], M Maltoni [21], A Marchionni [3], T Marrodán Undagoitia [15], J Marteau [1], A Meregaglia [3], M Messina [14], M Mezzetto [22], A Mirizzi [17,23], L Mosca [9], U Moser [14], A Müller [3], G Natterer [3], L Oberauer [15], P Otiougova [3], T Patzak [10], J Peltoniemi [13], W Potzel [15], C Pistillo [14], G G Raffelt [17], E Rondio [24], M Roos [25], B Rossi [14], A Rubbia [3], N Savvinov [14], T Schwetz [26], J Sobczyk [27], N J C Spooner [19], D Stefan [28], A Tonazzo [10], W Trzaska [2], J Ulbricht [3], C Volpe [29], J Winter [15], M Wurm [15], A Zalewska [28] and R Zimmermann [12]

[1] IPNL, Université Claude Bernard Lyon 1, CNRS/IN2P3, 69622 Villeurbanne, France
[2] Department of Physics, University of Jyväskylä, Finland
[3] Institut für Teilchenphysik, ETHZ, Zürich, Switzerland
[4] Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia
[5] CEA - Saclay, Gif sur Yvette and APC Paris, France
[6] Dpto Fisica Teorica y del Cosmos & C.A.F.P.E., Universidad de Granada, Spain
[7] Centre de Physique des Particules de Marseille (CPPM), IN2P3-CNRS et Université d'Aix-Marseille II, Marseille, France
[8] LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
[9] CEA - Saclay, Gif sur Yvette, France
[10] Astroparticule et Cosmologie (APC), CNRS, Université Paris VII, CEA, Observatoire de Paris, Paris, France
[11] Laboratoire de Physique Nucléaire et des Hautes Energies (LPNHE), IN2P3-CNRS et Universités Paris VI et Paris VII, Paris, France
[12] Universität Hamburg, Institut für Experimentalphysik, Hamburg, Germany
[13] CUPP, University of Oulu, Finland
[14] Laboratorium für Hochenergie Physik, Bern Universität, Bern, Switzerland
[15] Technische Universität München, Physik-Department E15, Garching, Germany
[16] Centro de Fisica Teorica de Particulas, Instituto Superior Tecnico, Departamento de Fisica, Lisboa, Portugal
[17] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

[18] Institute of Physics, University of Silesia, Katowice, Poland
[19] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[20] Max-Planck-Institut fuer Kernphysik, Heidelberg, Germany
[21] Departamento de Física Teórica & Instituto de Física Teórica, Facultad de Ciencias C-XI, Universidad Autónoma de Madrid, Cantoblanco, Madrid, Spain
[22] INFN Sezione di Padova, Padova, Italy
[23] INFN Sezione di Bari and Dipartimento di Fisica, Università di Bari, Bari, Italy
[24] A. Soltan Institute for Nuclear Studies, Warsaw, Poland
[25] Department of Physical Sciences, University of Helsinki, Finland
[26] CERN, Physics Department, Theory Division, Geneva, Switzerland
[27] Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland
[28] H. Niewodniczanski Institute of Nuclear Physics, Krakow, Poland
[29] Institut de Physique Nucleaire d'Orsay (IPNO), Groupe de Physique Theorique, Université de Paris-Sud XI, Orsay, France

E-mail: `campagne@lal.in2p3.fr`

Abstract.

This document reports on a series of experimental and theoretical studies conducted to assess the astro-particle physics potential of three future large-scale particle detectors proposed in Europe as next generation underground observatories. The proposed apparatus employ three different and, to some extent, complementary detection techniques: GLACIER (liquid Argon TPC), LENA (liquid scintillator) and MEMPHYS (water Cherenkov), based on the use of large mass of liquids as active detection media. The results of these studies are presented along with a critical discussion of the performance attainable by the three proposed approaches coupled to existing or planned underground laboratories, in relation to open and outstanding physics issues such as the search for matter instability, the detection of astrophysical- and geo-neutrinos and to the possible use of these detectors in future high-intensity neutrino beams.

Keywords : neutrino detectors, neutrino experiments, neutrino properties, solar and atmospheric neutrinos, supernova neutrinos, proton decay, wimp

PACS numbers: 13.30.a,14.20.Dh,14.60.Pq,26.65.t+,29.40.Gx,29.40.Ka,29.40.Mc,95.55.Vj,95.85.Ry, 97.60.Bw

Submitted to: *Journal of Cosmology and Astroparticle Physics*

1. Physics motivation

Several outstanding physics goals could be achieved by the next generation of large underground observatories in the domain of astro-particle and particle physics, neutrino astronomy and cosmology. Proton decay [1], in particular, is one of the most exciting prediction of Grand Unified Theories (for a review see [2]) aiming at the unification of fundamental forces in Nature. It remains today one of the most relevant open questions of particle physics. Its discovery would certainly represent a fundamental milestone, contributing to clarifying our understanding of the past and future evolution of the Universe.

Several experiments have been built and conducted to search for proton decay but they only yielded lower limits to the proton lifetime. The window between the predicted proton lifetime (in the simplest models typically below 10^{37} years) and that excluded by experiments [3] ($O(10^{33})$ years, depending on the channel) is within reach, and the demand to fill the gap grows with the progress in other domains of particle physics, astro-particle physics and cosmology. To some extent, also a negative result from next generation high-sensitivity experiments would be relevant to rule-out some of the theoretical models based on SU(5) and SO(10) gauge symmetry or to further constrain the range of allowed parameters. Identifying unambiguously proton decay and measuring its lifetime would set a firm scale for any Unified Theory, narrowing the phase space for possible models and their parameters. This will be a mandatory step to go forward beyond the Standard Model of elementary particles and interactions.

Another important physics subject is the physics of astrophysical neutrinos, as those from supernovae, from the Sun and from the interaction of primary cosmic-rays with the Earth's atmosphere. Neutrinos are above all important messengers from stars. Neutrino astronomy has a glorious although recent history, from the detection of solar neutrinos [4, 5, 6, 7, 8, 9, 10] to the observation of neutrinos from supernova explosion, [11, 12, 13], acknowledged by the Nobel Prizes awarded to M. Koshiba and R. Davis. These observations have given valuable information for a better understanding of the functioning of stars and of the properties of neutrinos. However, much more information could be obtained if the energy spectra of stellar neutrinos were known with higher accuracy. Specific neutrino observations could give detailed information on the conditions of the production zone, whether in the Sun or in a supernova. A supernova explosion in our galaxy would be extremely important as the evolution mechanism of the collapsed star is still a puzzle for astrophysics. An even more fascinating challenge would be observing neutrinos from extragalactic supernovae, either from identified sources or from a diffuse flux due to unidentified past supernova explosions.

Observing neutrinos produced in the atmosphere as cosmic-ray secondaries [14, 15, 16, 17, 18, 19, 20] gave the first compelling evidence for neutrino oscillation [21, 22], a process that unambiguously points to the existence of new physics. While today the puzzle of missing atmospheric neutrinos can be considered solved, there remain challenges related to the sub-dominant oscillation phenomena. In particular, precise measurements of atmospheric neutrinos with high statistics and small systematic errors [23] would help in resolving ambiguities and degeneracies that hamper the interpretation of other experiments, as those planned for future long baseline neutrino oscillation measurements.

Another example of outstanding open questions is that of the knowledge of the interior of the Earth. It may look hard to believe, but we know much better what happens inside the Sun than inside our own planet. There are very few messengers that can provide information, while a mere theory is not sufficient for building a credible model for the Earth. However, there is a new unexploited window to the Earth's interior, by observing neutrinos produced in the radioactive decays of heavy elements in the matter. Until now, only the KamLAND experiment [24] has been able to study these so-called geo-neutrinos opening the way to a completely new field of research. The small event rate, however, does not allow to draw significant conclusions.

The fascinating physics phenomena outlined above, in addition to other important subjects that we will address in the following, could be investigated by a new generation of multipurpose experiments based on improved detection techniques. The envisioned detectors must necessarily be very massive (and consequently large) due to the smallness of the cross-sections and to the low rate of signal events, and able to provide very low experimental background. The required signal to noise ratio can only be achieved in underground laboratories suitably shielded against cosmic-rays and environmental radioactivity. We can identify three different and, to large extent, complementary technologies capable to meet the challenge, based on large scale use of liquids for building large-size, volume-instrumented detectors

- Water Cherenkov. As the cheapest available (active) target material, water is the only liquid that is realistic for extremely large detectors, up to several hundreds or thousands of ktons; water Cherenkov detectors have sufficiently good resolution in energy, position and angle. The technology is well proven, as previously used for the IMB, Kamiokande and Super-Kamiokande experiments.
- Liquid scintillator. Experiments using a liquid scintillator as active target provide high-energy resolution and offer low-energy threshold. They are particularly attractive for low energy particle detection, as for example solar neutrinos and geo-neutrinos. Also liquid scintillator detectors feature a well established technology, already successfully applied at relatively large scale to the Borexino [25] and KamLAND [26] experiments.
- Liquid Argon Time Projection Chambers (LAr TPC). This detection technology has among the three the best performance in identifying the topology of interactions and decays of particles, thanks to the bubble-chamber-like imaging performance. Liquid Argon TPCs are very versatile and work well with a wide particle energy range. Experience on such detectors has been gained within the ICARUS project [27, 28].

Three experiments are proposed to employ the above detection techniques: MEMPHYS [29] for water Cherenkov, LENA [30, 31] for liquid scintillator and GLACIER [32, 33, 34, 35, 36] for Liquid Argon. In this paper we report on the study of the physics potential of the experiments and identify features of complementarity amongst the three techniques.

Needless to say, the availability of future neutrino beams from particle accelerators would provide an additional bonus to the above experiments. Measuring oscillations with artificial neutrinos (of well known kinematical features) with a sufficiently long baseline would allow to accurately determine the oscillation parameters (in particular the mixing angle θ_{13} and the possible CP violating phase in the mixing matrix). The envisaged detectors may then be used for observing neutrinos from the future Beta Beams and Super Beams in the optimal energy range for each experiment. A common example is a low-energy Beta Beam from CERN to MEMPHYS at Frejus, 130 km

Table 1. Basic parameters of the three detector (baseline) design.

	GLACIER	LENA	MEMPHYS
Detector dimensions			
type of cylinder	1 vert.	1 horiz.	$3 \div 5$ vert.
diam. (m)	70	30	65
length (m)	20	100	65
typical mass (kton)	100	50	$600 \div 800$
Active target and readout			
type of target	liq. Argon (boiling)	liq. scintillator	water (opt. 0.2% $GdCl_3$)
readout type	e^- drift: 2 perp. views, 10^5 channels, ampli. in gas phase; Cher. light: 27 000 8" PMTs, $\sim$ 20% coverage; Scint. light: 1000 8" PMTs	12 000 20" PMTs $\gtrsim$ 30% coverage	81 000 12" PMTs $\sim$ 30% coverage

away [37]. High energy beams have been suggested [38], favoring longer baselines of up to $O(2000\text{ km})$. The ultimate Neutrino Factory facility will require a magnetized detector to fully exploit the simultaneous availability of neutrinos and antineutrinos. This subject is however beyond the scope of the present study.

Finally, there is a possibility of (and the hope for) unexpected discoveries. The history of physics has shown that several experiments have made their glory with discoveries in research fields that were outside the original goals of the experiments. Just to quote an example, we can mention the Kamiokande detector, mainly designed to search for proton decay and actually contributing to the observation of atmospheric neutrino oscillations, to the clarification of the solar neutrino puzzle and to the first observation of supernova neutrinos [11, 39, 5, 15, 21]. All the three proposed experiments, thanks to their outstanding boost in mass and performance, will certainly provide a significant potential for surprises and unexpected discoveries.

2. Description of the three detectors

The three detectors' basic parameters are listed in Tab. 1. All of them have active targets of tens to hundreds kton mass and are to be installed in underground laboratories to be protected against background induced by cosmic-rays. As already said, the large size of the detectors is motivated by the extremely low cross-section of neutrinos and/or by the rareness of the interesting events searched for. Some details of the detectors are discussed in the following, while the matters related to the possible underground site are presented in Section 3.

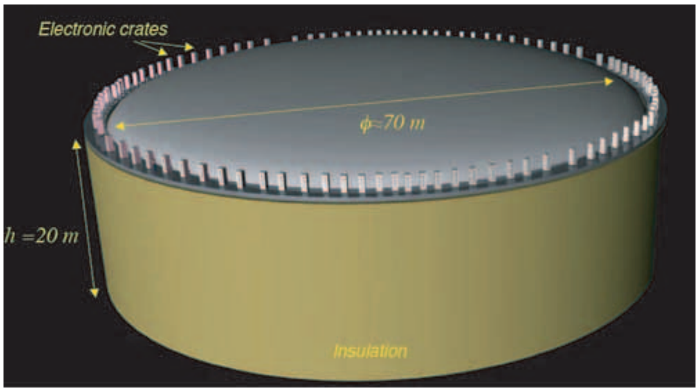

Figure 1. Artistic view of a 100 kton single-tank liquid Argon TPC detector. The electronic crates are located at the top of the dewar.

2.1. Liquid Argon TPC

GLACIER (Fig. 1) is the foreseen extrapolation up to 100 kton of the liquid Argon Time Projection Chamber technique. The detector can be mechanically subdivided into two parts, the liquid Argon tank and the inner detector instrumentation. For simplicity, we assume at this stage that the two aspects can be largely decoupled.

The basic idea behind this detector is to use a single 100 kton boiling liquid Argon cryogenic tank with cooling directly performed with liquid Argon (self-refrigerating). Events are reconstructed in 3D by using the information provided by ionization in liquid. The imaging capabilities and the excellent space resolution of the device make this detector an "electronic bubble chamber". The signal from scintillation and Cherenkov light readout complete the information contributing to the event reconstruction.

As far as light collection is concerned one can profit from the ICARUS R&D program that has shown that it is possible to operate photomultipliers (PMTs) directly immersed in the liquid Argon [27]. In order to be sensitive to deep UV (DUV) scintillation ($<$ 300nm), PMTs are coated with a wavelength shifter (WLS), for instance tetraphenyl-butadiene. About 1000 immersed phototubes with WLS would be used to identify the (isotropic and bright) scintillation light. To detect Cherenkov radiation about 27 000 8”-phototubes without WLS would provide a 20% coverage of the detector surface. The latter PMTs should have single photon counting capabilities in order to count the number of Cherenkov photons.

Charge amplification and an extreme liquid purity against electronegative compounds (although attainable by commercial purification systems) is needed to allow long drift distances of the ionization/imaging electrons ($\approx$ 20 m). For this reason, the detector will run in the so-called bi-phase mode. Namely, drifting electrons produced in the liquid phase are extracted into the gas phase with the help of an electric field and amplified in order to compensate the charge loss due to attenuation along the drift path. The final charge signal is then read out by means of Large Electron Multiplier (LEM) devices, providing X-Y information. The Z coordinate is given by the drift time measurement, proportional to the drift length. A possible extension of the present detector design envisages the immersion of the sensitive