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

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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.

KEYWORDS: Keyword1; Keyword2; Keyword3.

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1. Physics motivation

Our last citation [1].....

The RMS error is σ...

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 [2], in particular, is one of the most exciting prediction of Grand Unified Theories (for a review see [3]) 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 [4] ($O(10^{33})$ 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 [5, 6, 7, 8, 9, 10, 11] to the observation of neutrinos from supernova explosion, [12, 13, 14], 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

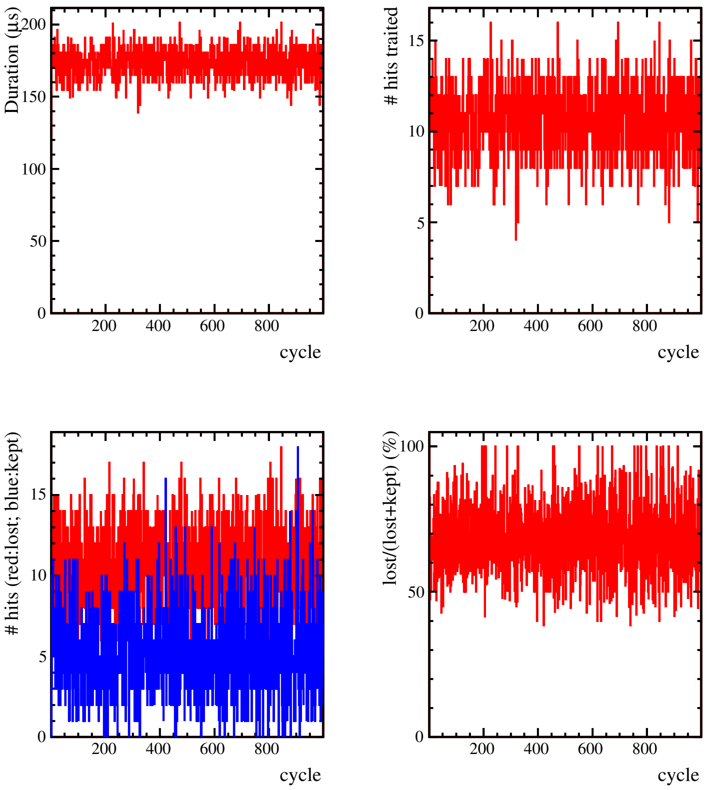
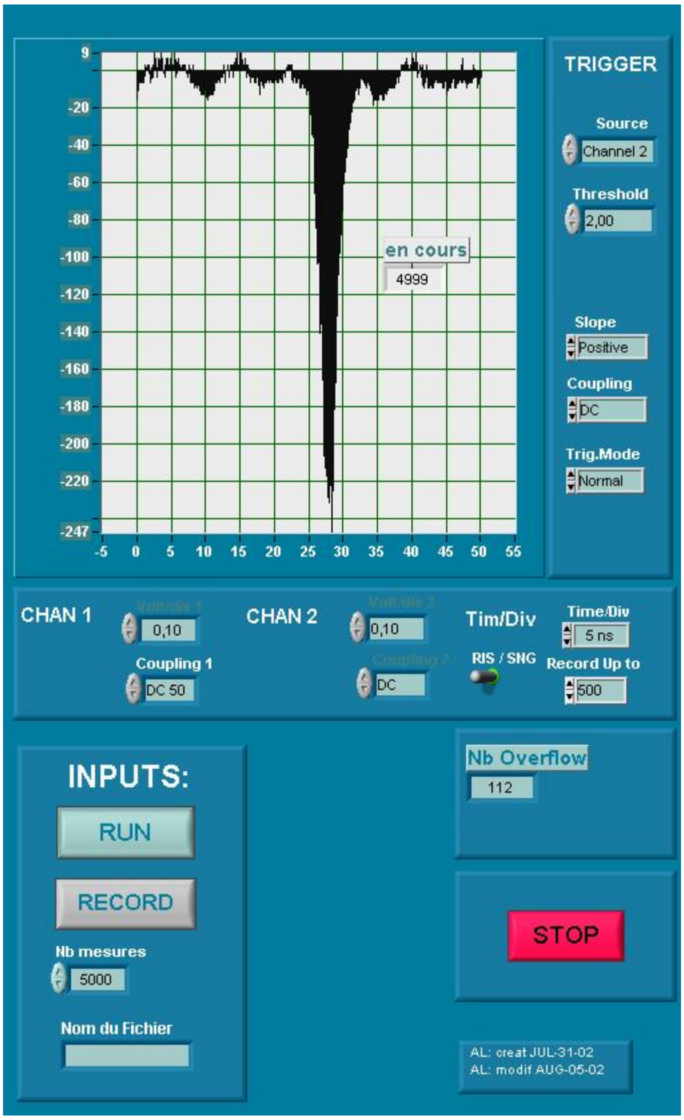


Figure 1. Example of figure PDF

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 [15, 16, 17, 18, 19, 20, 21] gave the first compelling evidence for neutrino oscillation [22, 23], 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 [24] 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 [25] has been able to study these so-called geo-neutrinos opening the way to a completely new field of research.



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Threshold: 2,00

Slope: Positive

Coupling: DC

Trig.Mode: Normal

Volt/div 1: 0,10

Coupling 1: DC 50

Volt/div 2: 0,10

Coupling 2: DC

RIS / SNG

Time/Div: 5 ns

Record Up to: 500

Nb Overflow: 112

Nb mesures: 5000

Nom du Fichier:

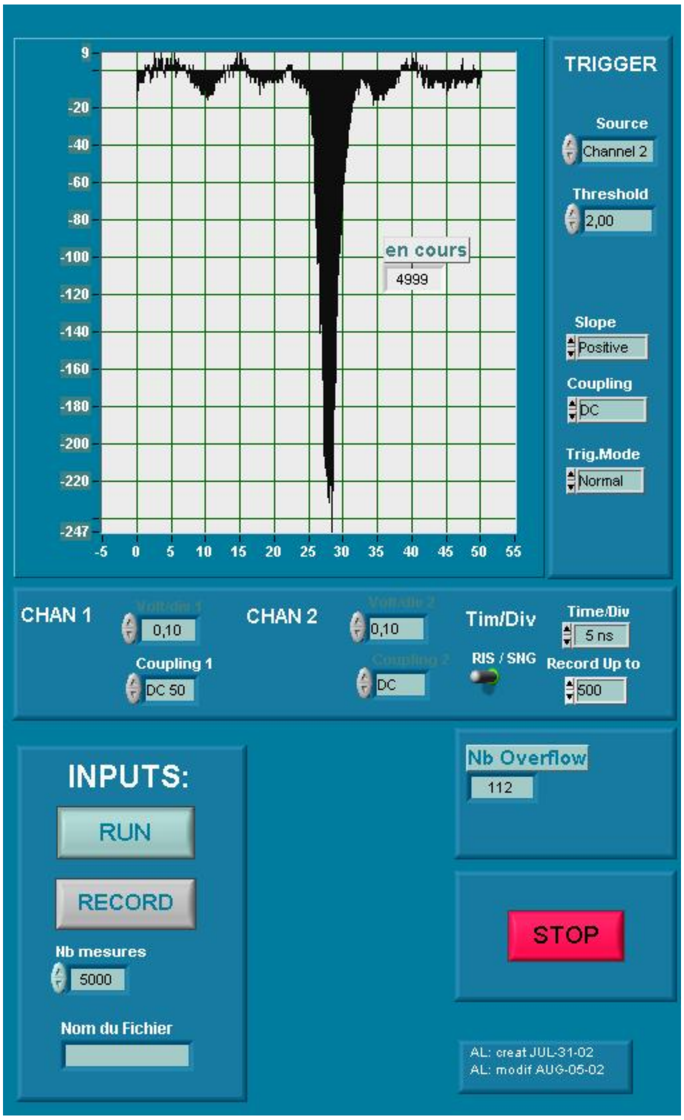
AL: creat JUL-31-02
AL: modif AUG-05-02

Figure 2. Example 2

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



en cours 4999

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Trig.Mode: Normal

Volt/div 1: 0,10

Coupling 1: DC 50

Volt/div 2: 0,10

Coupling 2: DC

RIS / SNG

Time/Div: 5 ns

Record Up to: 500

Nb Overflow: 112

Nb mesures: 5000

Nom du Fichier:

AL: creat JUL-31-02
AL: modif AUG-05-02

Figure 3. Example figure JPEG

that is realistic for extremely large detectors, up to several hundreds or thousands of ktons; 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 [26] and KamLAND [27] 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 [28, 29].

Three experiments are proposed to employ the above detection techniques: MEMPHYS [30] for WC, LENA [31, 32] for liquid scintillator and GLACIER [33, 34, 35, 36, 37] 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 Beta Beam from CERN to MEMPHYS at Frejus, 130 km away [38]. High energy beams have been suggested [39], favoring longer baselines of up to O(2000 km). An exhaustive review on the different Beta Beam scenario can be found in the reference [40]. 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 [12, 41, 6, 16, 22]. 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.

Acknowledgments

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References

References

[1] B. Genolini *et. al.*, “PMm2: large photomultipliers and innovative electronics for the next-generation neutrino experiments” 0811.2681.

[2] J. C. Pati and A. Salam, “Is Baryon Number Conserved?” *Phys. Rev. Lett.* **31** (1973) 661–664.

[3] P. Nath and P. Fileviez Pérez, “Proton stability in grand unified theories, in strings, and in branes” *Phys. Rept.* **441** (2007) 191–317 [hep-ph/0601023].

[4] **Super-Kamiokande** Collaboration, K. Kobayashi *et. al.*, “Search for nucleon decay via modes favored by supersymmetric grand unification models in Super-Kamiokande-I” *Phys. Rev.* **D72** (2005) 052007 [hep-ex/0502026].

[5] J. Davis, Raymond, D. S. Harmer and K. C. Hoffman, “Search for neutrinos from the sun” *Phys. Rev. Lett.* **20** (1968) 1205–1209.

[6] **Kamiokande-II** Collaboration, K. S. Hirata *et. al.*, “Observation of B-8 solar neutrinos in the Kamiokande-II detector” *Phys. Rev. Lett.* **63** (1989) 16.

[7] **GALLEX** Collaboration, P. Anselmann *et. al.*, “Solar neutrinos observed by GALLEX at Gran Sasso.” *Phys. Lett.* **B285** (1992) 376–389.

[8] D. N. Abdurashitov *et. al.*, “Results from SAGE” *Phys. Lett.* **B328** (1994) 234–248.

[9] **Super-Kamiokande** Collaboration, M. B. Smy, “Solar neutrino precision measurements using all 1496 days of Super-Kamiokande-I data” *Nucl. Phys. Proc. Suppl.* **118** (2003) 25–32 [hep-ex/0208004].

[10] **SNO** Collaboration, B. Aharmim *et. al.*, “Electron energy spectra, fluxes, and day-night asymmetries of B-8 solar neutrinos from the 391-day salt phase SNO data set” *Phys. Rev.* **C72** (2005) 055502 [nucl-ex/0502021].

[11] **GNO** Collaboration, M. Altmann *et. al.*, “Complete results for five years of GNO solar neutrino observations” *Phys. Lett.* **B616** (2005) 174–190 [hep-ex/0504037].

[12] **Kamiokande-II** Collaboration, K. Hirata *et. al.*, “Observation of a neutrino burs from the supernova SN1987a” *Phys. Rev. Lett.* **58** (1987) 1490–1493.

[13] R. M. Bionta *et. al.*, “Observation of a neutrino burst in coincidence with supernova SN1987A in the Large Magellanic Clound” *Phys. Rev. Lett.* **58** (1987) 1494.

[14] E. N. Alekseev, L. N. Alekseeva, I. V. Krivosheina and V. I. Volchenko, “Detection of the neutrino signal from SN1987A in the LMC using the INR Baksan underground scintillator telescope” *Phys. Lett.* **B205** (1988) 209–214.

[15] **The NUSEX** Collaboration, M. Aglietta *et. al.*, “Experimental study of atmospheric neutrino flux in the NUSEX experiment” *Europhys. Lett.* **8** (1989) 611–614.

[16] **Kamiokande-II** Collaboration, K. S. Hirata *et. al.*, “Experimental study of the atmospheric neutrino flux” *Phys. Lett.* **B205** (1988) 416.

[17] **Kamiokande-II** Collaboration, K. S. Hirata *et. al.*, “Observation of a small atmospheric ν_μ/ν_e ratio in Kamiokande” *Phys. Lett.* **B280** (1992) 146–152.

[18] R. Becker-Szendy *et. al.*, "The Electron-neutrino and muon-neutrino content of the atmospheric flux" *Phys. Rev.* **D46** (1992) 3720–3724.

[19] **Fréjus** Collaboration, K. Daum *et. al.*, "Determination of the atmospheric neutrino spectra with the Fréjus detector" *Z. Phys.* **C66** (1995) 417–428.

[20] **Soudan-2** Collaboration, W. W. M. Allison *et. al.*, "The atmospheric neutrino flavor ratio from a 3.9 fiducial kiloton-year exposure of Soudan 2" *Phys. Lett.* **B449** (1999) 137–144 [`hep-ex/9901024`].

[21] **Super-Kamiokande** Collaboration, Y. Ashie *et. al.*, "A measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I" *Phys. Rev.* **D71** (2005) 112005 [`hep-ex/0501064`].

[22] **Super-Kamiokande** Collaboration, Y. Fukuda *et. al.*, "Evidence for oscillation of atmospheric neutrinos" *Phys. Rev. Lett.* **81** (1998) 1562–1567 [`hep-ex/9807003`].

[23] T. Kajita, "Discovery of neutrino oscillations" *Rept. Prog. Phys.* **69** (2006) 1607–1635.

[24] T. Tabarelli de Fatis, "Prospects of measuring $sin^2(2\theta_{13})$ and the sign of Δm^2 with a massive magnetized detector for atmospheric neutrinos" *Eur. Phys. J.* **C24** (2002) 43–50 [`hep-ph/0202232`].

[25] T. Araki *et. al.*, "Experimental investigation of geologically produced antineutrinos with KamLAND" *Nature* **436** (2005) 499–503.

[26] **Borexino** Collaboration, H. O. Back *et. al.*, "Phenylxylylethane (PXE): A high-density, high-flashpoint organic liquid scintillator for applications in low-energy particle and astrophysics experiments" `physics/0408032`.

[27] **KamLAND** Collaboration, T. Araki *et. al.*, "Measurement of neutrino oscillation with KamLAND: Evidence of spectral distortion" *Phys. Rev. Lett.* **94** (2005) 081801 [`hep-ex/0406035`].

[28] **ICARUS** Collaboration, S. Amerio *et. al.*, "Design, construction and tests of the ICARUS T600 detector" *Nucl. Instrum. Meth.* **A527** (2004) 329–410.

[29] **ICARUS** Collaboration, F. Arneodo *et. al.*, "The ICARUS experiment, a second-generation proton decay experiment and neutrino observatory at the Gran Sasso Laboratory" `hep-ex/0103008`.

[30] A. de Bellefon *et. al.*, "MEMPHYS: A large scale water Cherenkov detector at Fréjus" `hep-ex/0607026`.

[31] L. Oberauer, F. von Feilitzsch and W. Potzel, "A large liquid scintillator detector for low-energy neutrino astronomy" *Nucl. Phys. Proc. Suppl.* **138** (2005) 108–111.

[32] T. Marrodán Undagoitia *et. al.*, "Low energy neutrino astronomy with the large liquid scintillator detector LENA" *Prog. Part. Nucl. Phys.* **57** (2006) 283 [`hep-ph/0605229`].

[33] A. Rubbia, "Experiments for CP-violation: A giant liquid argon scintillation, Cherenkov and charge imaging experiment?" `hep-ph/0402110`.

[34] A. Rubbia, "Review of massive underground detectors" `hep-ph/0407297`.

[35] A. Ereditato and A. Rubbia, "Ideas for future liquid argon detectors" *Nucl. Phys. Proc. Suppl.* **139** (2005) 301–310 [`hep-ph/0409143`].

[36] A. Ereditato and A. Rubbia, "The liquid argon TPC: A powerful detector for future neutrino experiments and proton decay searches" *Nucl. Phys. Proc. Suppl.* **154** (2006) 163–178 [`hep-ph/0509022`].

[37] A. Ereditato and A. Rubbia, “Conceptual design of a scalable multi-kton superconducting magnetized liquid argon TPC” *Nucl. Phys. Proc. Suppl.* **155** (2006) 233–236 [`hep-ph/0510131`].

[38] J. E. Campagne, M. Maltoni, M. Mezzetto and T. Schwetz, “Physics potential of the CERN-MEMPHYS neutrino oscillation project” *JHEP* **04** (2007) 003 [`hep-ph/0603172`].

[39] C. Rubbia, A. Ferrari, Y. Kadi and V. Vlachoudis, “Beam cooling with ionisation losses” `hep-ph/0602032`.

[40] C. Volpe, “Topical review on ’beta-beams”’ *J. Phys.* **G34** (2007) R1–R44 [`hep-ph/0605033`].

[41] K. S. Hirata *et. al.*, “Observation in the Kamiokande-II detector of the neutrino burst from supernova SN1987A” *Phys. Rev.* **D38** (1988) 448–458.