Neutrino astrophysics and proton decay searches at MEMPHYS

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We provide an overview of the potential for a megaton scale water Čerenkov detector installed at the Fréjus underground site to explore nucleon decay and neutrinos from supernovae and other cosmological sources.

1. INTRODUCTION

A megaton-scale water Čerenkov detector could be installed at the Modane underground Laboratory, in the Fréjus tunnel connecting France to Italy. A document of interest for this project, called MEMPHYS (MEgaton Mass PHYSics), has recently been published [1]. Further information and the detailed report on excavation studies can be found on the www site [2] or in another presentation given at this conference [3].

The baseline of the proposed detectors consists of 3 cylindrical cavities, about 65 m each in height and diameter, filled with water to provide a fiducial mass of 440 kton. Each cavity is equipped with ∼80k 12" PMTs providing 30% optical coverage (equivalent, in terms of number of PEs, to the 40% coverage with 20" PMTs of Super-Kamiokande [4]).

A small amount of Gadolinium salt in the water [5] would enhance the detector capabilities with identification of the neutron from inverse-β $\bar{\nu}_e$ interactions, thus reducing the background and allowing to lower the threshold for physics studies in this channel.

Such a detector would have competitive capabilities for neutrino oscillation physics, as discussed elsewhere [6]. In addition, it would reach a sensitivity on the proton lifetime close to the predictions of most supersymmetric or higher dimension grand unified theories and it would explore neutrinos from supernovae and from other cosmological sources. An overview of these items is presented in the following.

2. SUPERNOVA EXPLOSION

When a massive star core collapses, 99% of the energy (10^{53} erg) is emitted as neutrinos of all species over a time interval of ∼10 s. These neutrinos are observed in a water Čerenkov detector through inverse-β decay, elastic scattering on electrons or neutral current interactions on oxygen nuclei (see [7] or [1] for details).

The expected number of neutrino events from a SuperNova (SN) explosion in a large water-Čerenkov detector has been computed in [7]. The large mass of a MEMPHYS implies that the collected sample would outnumber that of all other existing detectors, ensuring sensitivity to SN occurring throughout the local group of galaxies. A handful of events might be seen even at a distance as large as 3 Mpc.

For a SN in our galaxy, the huge statistics of neutrino interactions ($\sim 2\times10^5$ for a SN at 10 kpc), mainly detected though the inverse-β reaction, would allow to perform spectral analyses of the neutrino flux in energy, time and composition, thus gaining insight on the SN explosion mechanism, on neutrino propagation parameters and on neutrino properties. A selection of examples, forcedly incomplete, is presented in the rest of this section.

It has been shown in [8] that a detector like the proposed one would allow precise determination of some parameters characerising the time-integrated neutrino spectra. For an interesting range of values of the neutrino mixing angle θ_{13}, this would make it possible to distinguish normal from inverted neutrino mass hierarchy or to obtain measurements of $\sin^2\theta_{13}$ with a sensitivity at least an order of magnitude better than planned terrestrial experiments [9].

As neutrinos propagate out of the SN core, they can cross resonances in the time-profile of matter density which can induce time-dependent matter effects on their oscillations [10][11]. Depending on the neutrino mixing parameters, such effects could be observed from the peak structure in some time-dependent energy obervables [12], or more simply by comparing the arrival time in different energy bins [7].

Earth matter effects are another factor that can induce modulations of the energy spectrum of ν_e or $\bar{\nu}_e$, measurable at a single detector through a Fourier analysis [13]. In water Čerenkov, due to the poor energy resolution, the effect would only be observable with a very large statistics, which will actually be available at a large detector such as MEMPHYS.

Finally, the neutronization burst occurring in the first ∼25 ms after the core collapse, where 1% of the explosion energy is released as ν_e, could be observed from the time structure of $\nu_e e^-$ elastic scattering events [14].

For SN explosions outside our galaxy, although the number of events from a single explosion at such large distances would be small, the signal could be identified with the request to observe at least two events within a time window comparable to the neutrino emission time-scale (∼10 sec) [15]. In a MEMPHYS-type detector, a SN 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 act as a precise time trigger for other SN detectors. Neutrino detection with a time coincidence would also allow the detection of SN which are either heavily obscured by dust or are optically dark due to prompt black hole formation.

3. DIFFUSE SUPERNOVA NEUTRINOS

An upper limit on the flux of neutrinos coming from all past core-collapse SN (the Diffuse Supernova Neutrinos, DSN) has been set by the Super-Kamiokande experiment [16], however most of the estimates are below this limit and therefore DSN detection thorough inverse-β decay appears to be feasible at a megaton-scale water Čerenkov detector. A few tens of events can be observed in few years, accoordign to the most conservative estimates [17].

As pointed out in [7], with addition of Gadolinium the detection threshold could be lowered significantly 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 it would even be possible to distinguish between different theoretical predictions. An analysis of of the information that could be gained on DSN spectrum parameters with a Gd-loaded water Čerenkov detector has been carried out in [18]. Detailed studies on characterization of the backgrounds, however, are still needed.

If DSN decay, the modifications of the spectrum could be observed by MEMPHYS [19].

DSN measurements could also provide information on dark energy parameters [20].

4. ASTROPHYSICAL SOURCES OF NEUTRINOS

MEMPHYS will be able to observe a statistically significant signal from low-energy neutrinos accompanying the ultra-high-energy neutrino and optical emission from GRBs [21].

It could also detect the neutrinos emitted from black-hole formation in the collapse of a star too massive to generate a supernova [22].

In addition, MEMPHYS could detect muons from the interaction in the Earth of neutrinos coming from below, originated from point sources such as AGNs, from WIMPs annihilating in the Earth, Sun or Galaxy, and high energy neutrinos from GRBs [23].

5. PROTON DECAY

One of the most important physics items at a large scale water Čerenkov detector is the search for proton decay, forbidden in the Standard Model and with a current experimental limit set by Super-Kamiokande [24].

Lifetimes of 10^{34}-10^{36} years are predicted by non-SUSY GUTs, favouring the decay channel $p \to e^+\pi^0$. SUSY GUTs predict lifetimes 10^{33}-10^{34} years, depending on SUSY particle spectrum, Higgs sector and fermion masses, with the decay channel $p \to \bar{\nu}K^+$ favoured. A complete review can be found in [25].

For proton decay studies, no specific simulation for MEMPHYS has been carried out yet. We therefore rely on the study done for a similar proposal in the US, UNO [23], adapting the results to MEMPHYS (which has an overall better coverage) when possible.

Following the UNO study, the detection efficiency for $e^+\pi^0$ (3 showering rings event) is ∼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. Based on these efficiencies and background levels, 10^{35} years partial lifetime could be reached at the 90% CL for a 5 Mt·yr exposure with MEMPHYS.

A megaton-scale water Čerenkov would outperform any other proposed detector in the search for this proton decay channel. This is actually one of the strongest motivations for this project.

In the $\bar{\nu}K^+$ channel, since the K^+ is below the Čerenkov threshold, detection is via its decay products. With the efficiency and background conditions estimated by UNO and using Super-Kamiokande performances, a 5 Mt·yr MEMPHYS exposure would allow to reach $2{\times}10^{34}$ years partial lifetime.

6. CONCLUSIONS AND OUTLOOK

A megaton-scale water Čerenkov detector could cover a variety of astroparticle physics topics, mainly related to the studies of neutrinos from supernovae. It would also set stringent limits on the proton decay lifetime.

Its potential would be best exploited in combination with other large mass detectors based on complementary technique, such as liquid scintillator and liquid argon. A european proposal for installing the three detectors at the Fréjus underground site [26][3] is being finalized.

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