A large liquid scintillator detector for low-energy neutrino astronomy

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The potential of a large liquid scintillator detector in an underground laboratory for supernova neutrino detection, solar neutrino detection, and the search for proton decay $p \rightarrow K^+\nu$ is discussed.

1. INTRODUCTION

In this paper we propose a large liquid scintillator detector for low-energy neutrino astronomy (LENA). With LENA, one may aim at important topics like time-resolved flavor-specific detection of galactic supernova neutrinos, supernova relic neutrinos, high statistic solar neutrino spectroscopy, detection of terrestrial neutrinos, long baseline neutrino experiments, and proton decay. With this scientific program, fundamental aspects in particle astrophysics, as well as elementary particle and geophysics, would be addressed. Here we present the detector characteristics of LENA and discuss its potential for supernova physics, solar physics, and proton decay searches.

2. DETECTOR CHARACTERISTICS

The detector is proposed to consist of a large volume liquid scintillator with cylindrical shape, approximately 30 m in diameter and 90 m in length, equipped with a photomultiplier (PM) coverage of about 30%. This can be achieved with about 12000 PMs with 50 cm diameter each. The detector could be placed for instance under sea close to the coast at Pylos (Greece) at the deepest site in Europe (≈5000 m) or at the center of underground physics in Pyhäsalmi (CUPP, Finland) in 1400 m depth of rock (≈4060 mwe). Both sites are favored as being far away from nuclear power plants, which may significantly contribute to the $\bar{\nu_e}$ background in the search for relic supernovae neutrinos.

We propose PXE (phenyl-o-xylylethane) as scintillator for LENA. It has been investigated in the R&D of BOREXINO [1]. PXE has a high density of 0.99g/cm^3 and shows a high light yield of about 88% relative to pseudocumene. According to UN regulations, PXE is legally non-hazardous for transportation purposes. It is safe to handle due to its high flash-point of 145^{o}C. A light attenuation length of about 12 m at 450 nm wavelength has been achieved [2]. We estimate a photoelectron yield of about 120 pe/MeV for a beta-like event which occurs in the center of LENA. Hence, for the discussion below an energy resolution $\delta E/E = 0.1(E/MeV)^{-1/2}$ can be assumed. A position resolution $\delta r = 25cm(E/MeV)^{-1/2}$ for single events can be expected. After purification in Si-gel columns the mass-concentrations of ^{238}U and ^{232}Th have been measured via NAA to be below 10^{-17} and 2×10^{-16}, respectively [3]. We conclude that, with PXE, a non-hazardous, pure scintillator with high light yield and large attenuation length would be available for LENA.

3. SUPERNOVA NEUTRINOS

3.1. Galactic supernova neutrino detection

In case of a supernova at the center of our galaxy, ≈15000 ν-events in LENA can be expected. Using an organic scintillator containing ^{12}C allows the distinct flavor-specific neutrino and antineutrino detection by the following reactions:

1) $\bar{\nu_e} + p \rightarrow e^+ + n$ (Q = 1.8 MeV),
2) $\bar{\nu_e} +^{12} C \rightarrow e^+ +^{12} B$ (Q = 17.3 MeV),
3) $\nu_e +^{12} C \rightarrow^{12} N + e^-$ (Q = 13.4 MeV),
4) $\nu_x +^{12} C \rightarrow^{12} C^* + \nu_x$ with $^{12}C^* \rightarrow^{12} C + \gamma$

($E_\gamma = 15.1$ MeV), and
5) $\nu_x + p \rightarrow \nu_x + p$ (elastic scattering).
The spectral $\bar{\nu_e}$-contribution can be identified via the first cc-reaction, utilizing the delayed coincidence between the prompt positron and the succeeding neutron capture on hydrogen. This is the dominant reaction mode with the highest cross-section, and one would expect ca. 7000 events.

With this information the ν_e-spectrum above 13.4 MeV can be disentangled from the cc-reactions (2) and (3) which yield an event number of ≈500 and ≈100, respectively. Both reactions can be tagged by the re-decay of the daughter nuclei ^{12}B (β^-, $T_{1/2} = 20ms$) and ^{12}N (β^+, $T_{1/2} = 11ms$). All ν-flavors participate in the nc-interaction (4), which yields information about the total SN-ν flux. Here about 4000 events may be expected. Elastic scattering of all flavors on hydrogen (5) will lead to an intense (≈2200 events) low-energy signal due to recoil protons [4]. Observation of this interaction type becomes feasible as the detector threshold can be as low as ≈0.2 MeV (equivalent to ca. 25 pe for an event in the center). This signal can be clearly separated from the 'high-energy' pulses from reactions (1) to (4). The measured proton recoil spectrum reflects the incoming SN-ν spectrum. If the mean energies of ν_μ, ν_τ are above the mean energy of ν_e, the signal above threshold should be dominated by muon- and tau-νs. In addition, elastic ν-scattering off electrons would be observed. This signal would yield a low-energy supplement of the events seen in large water Cherenkov detectors like SuperKamiokande.

Observation of such a burst would allow researchers to measure the time development of the specific ν-fluxes in a Supernova and would reveal important details of the explosion mechanism. In addition, the $\bar{\nu_e}$ energy spectrum would show wiggles which are caused by oscillation matter effects when the neutrinos cross the Earth before entering the detector. These wiggles are observable in LENA due to the good energy resolution and statistics, and they would reveal information about ν-oscillation parameters as well as the mass hierarchy (for details see [5]).

3.2. Supernova relic neutrino detection

It is generally believed that supernova core-collapses have traced the star formation history in the Universe. In these explosions a great number of SRN-νs must have been emitted. The comparison of the experimentally observed SRN-spectrum with the predicted results of models will deliver valuable information on the star formation history in the Universe. Current models on the star formation rate contain various uncertainties, especially at high redshift regions (see e.g., [6] and refs. therein). The supernova rate is expected to be proportional to the star formation rate, as the lifetime of progenitors of core-collapse supernovae is much shorter than the cosmological time scale.

The SRN-flux determination is one of the targets of LENA. The current best limit on SRN comes from the SuperKamiokande detector [7], giving an upper limit of 1.2 cm^{-2}s^{-1} for $\bar{\nu_e}$ with a threshold of 19.3 MeV. With LENA the sensitivity for the SRN search should be drastically improved, as the delayed coincidence between the prompt positron and the captured neutron in the inverse beta reaction can be utilized. This strongly reduces the background and it should be possible to reach an energy threshold of ≈9 MeV. A lower threshold is prohibited by the ubiquitous $\bar{\nu_e}$s from nuclear power plants. According to the most recent models [6], the predicted SRN flux at 10 MeV is about 0.6 cm^{-2}sec^{-1}MeV^{-1} and LENA should observe an event rate of about 4/year.

4. SOLAR NEUTRINOS

The precise knowledge of the functionality of the solar energy release is a fundamental cornerstone in astrophysics. It is notable that the actual results of solar ν-experiments still would allow a CNO-contribution which exceeds the standard value by a factor ≈ 5 [8]. One expects that BOREXINO and KamLAND will measure the solar ^{7}Be-ν flux. However, the fluxes of pep-, as well as CNO-ν, are faint and the unavoidable background due to cosmic rays will make the measurement very difficult (details in [9]). With LENA, the solar ν-rates would be ca. 5400/d in a fiducial volume of about 22,000m^3 for ^{7}Be-ν, 150/d for pep-ν, and 210/d for CNO-ν. The high statistics would help in the ν-signal identification, as the annual 7% change due to the eccentricity of the Earth's orbit should be observable.

The ^{7}Be-ν rate could be determined with an accuracy of ca. 5% after only one year of measurement. From this measurement, together with the knowledge of the solar luminosity and ν-oscillation parameters, the fundamental pp-flux can be determined with an accuracy of better than 0.5% [10]. Important astrophysical parameters like the R_{34}/R_{33} branching ratio could be measured to a precision of about 1% [10].

Due to the MSW-effect, the survival probability of ν_es created in the solar center depends on the energy and on the density profile of the sun. The high-statistic measurement of ^{7}Be-ν's with LENA would allow researchers to test on temporal fluctuations of the solar density profile with high precision. Such temporal density fluctuations could be created by solar g-mode waves, which are not observed so far by helioseismology. Following the arguments from [11] a density fluctuation of 1.5% should result in a ^{7}Be-ν flux change of about 10%.

5. PROTON DECAY

In the search for the decay mode $p \rightarrow K^+\nu$, which is favored by SUSY models, water Cherenkov detectors are limited as the energy of the Kaon is below the Cherenkov threshold. In LENA this decay mode is visible. With a probability of 63.5% the Kaon decays via $K^+ \rightarrow \mu^+\nu_\mu$, and in this case the scenario for a signal in LENA would be:
i) a prompt mono-energetic K^+ (T=105 MeV), and
ii) a short delayed (τ=12.8 ns) mono-energetic μ^+ (T=152 MeV),
iii) a long delayed (τ=2.2 ms) e^+ from the following μ^+ decay.

With a probability of 21.2% the Kaon decays via $K^+ \rightarrow \pi^+\pi^0$, and in this case the scenario for a signal in LENA would be:
i) a prompt mono-energetic K^+ (T=105 MeV),
ii) a short delayed mono-energetic π^+ (T=108 MeV) accompanied by an electromagnetic shower due to the 2-γ decay of the π^0 (E=246 MeV),
iii) a short delayed (τ=26 ns) mono-energetic μ^+ with T = 4 MeV from the π^+ decay, and
iv) a long delayed (τ=2.2 ms) e^+ from the μ^+ decay.

Due to the good energy resolution, the fast detector response, and position reconstruction, the search for the proton decay into this channel should be performed basically background-free with a high efficiency. For LENA the reachable sensitivity for the proton decay $p \rightarrow K^+\nu$ could be close to a lifetime limit between 10^{34} and 10^{35} years after a measuring time of 10 years. The minimal SUSY SU(5) model predicts the decay mode to be dominant with a partial lifetime varying from 10^{29} to 10^{35} years [12]. The actual best limit on this decay mode from SuperKamiokande is 6.7×10^{32} y (90% cl) [13]. LENA could detect further interesting nucleon decay modes which are 'invisible' for Cherenkov detectors. Details can be found in [14].

REFERENCES

1. M. Göger, S. Schönert, Borexino Coll., to be submitted to Nucl. Instr. & Methods.
2. S. Schönert, private communication.
3. R. von Hentig *et al.*, Nucl. Phys. B (Proc. Suppl.) 78 (1999) 115.
4. J. Beacom, Nucl. Phys. B (Proc. Suppl.) 118 (2003) 307.
5. A. Dighe et al., hep-ph/0304150, JCAP 0306 (2003) 6.
6. S. Ando *et al.*, Astropart. Phys. 18 (2003) 307.
7. SuperKamiokande Coll., Phys. Rev. Lett. 90 (2003) 061101.
8. J. Bahcall *et al.*, Phys. Rev. Lett. 90 (2003) 131301.
9. T. Hagner *et al.*, Astropart. Phys. 14 (2000) 33.
10. J. Bahcall, C. Pena-Garay, hep-ph/0305159, acc. for publ. in JHEP.
11. A. Balantekin, H. Yuksel, hep-ph/0303169, Phys. Rev. D 68 (2003) 013006.
12. K.S. Babu, J.C. Pati, F. Wilczek, Phys. Lett. B 423 (1998) 337.
13. SuperKamiokande Collab., Phys. Rev. Lett.

83 (1999) 1529.
14. R. Swoboda, these proceedings, TAUP (2003).