LENA: A multipurpose detector for low energy neutrino astronomy and proton decay

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Abstract.
The status of the feasibility studies for the proposed large liquid-scintillator detector LENA (Low Energy Neutrino Astronomy) is reported. Recent technical investigations of optical properties of possible scintillator mixtures are described and the physics potential concerning supernova, solar and geophysics as well as proton decay is reviewed.

1. Introduction
Organic liquid-scintillator detectors, as KamLAND [1] or Borexino [2], have already shown the great physics potential of such a technology. The LENA (Low Energy Neutrino Astronomy) project suggests a 50 kt liquid scintillator detector for further investigations of low-energy neutrinos (from supernovae, the Sun, our Earth or from artificial sources) and for the search for proton decay.

2. Current detector design
The detector design has been described elsewhere [3][4]. It is based on a cylinder with a diameter of 30 m and a length of approximately 100 m. To look at the scintillation light, the inner volume will be instrumented with ~13 000 photomultiplier tubes providing a surface coverage of ~30% which results in a photoelectron (pe) efficiency of at least 10² pe/MeV. Thus, sub-MeV neutrino astronomy becomes feasible. The inner volume will be filled with about 50 kt of liquid scintillator, the exact composition being still under discussion. In the outer part, a water Cherenkov detector will tag through-going muons. Most of the research areas mentioned above require a low background event rate. Thus, the detector should be placed underground at a depth of around 4 000 m.w.e.

3. Liquid scintillator feasibility studies
In the last years, intensive R&D on liquid scintillators and photo-sensors has been set up for LENA. Optical properties of various scintillator mixtures have been tested to guarantee good energy resolution, high light collection, fast timing and precise position reconstruction. The
solvents PXE, LAB and Dodecane, and the solutes PPO, pTP, bisMSB and PMP, mixed in different concentrations [5][6] have been under investigation.

Experiments to investigate the light propagation have been performed and it has been shown that absorption and scattering lengths in the range of 20 m can be reached. These values correspond to an one-dimensional attenuation length of $\sim 10$ m. Monte Carlo calculations show [9] that for such a scintillator, a light yield of 180 pe/MeV would be obtained.

Furthermore, the light production has been studied in detail. Measurements concerning the fluorescence decay constants show that different scintillator mixtures have a strong influence on the time structure. Using the single-photon counting method, the time evolution of the scintillation-photon emission has been obtained. The spectrum can be fitted by three exponential decay times: for a mixture of PXE with 2 g/ℓ PPO, a shortest decay constant of around 3 ns has been found. For LAB with 2 g/ℓ PPO, typical values around 6 ns have been observed. Also for a mixture of pure Dodecan with 2 g/ℓ PPO a relatively slow time constant of about 5 ns was found. In addition, measurements of the time constants of PXE with different concentrations of PPO have been performed. The shortest time constant has been found for PXE with 6 g/ℓ PPO with $\sim 2.3$ ns, for smaller fluor concentrations the value increases as the energy transfer between PXE and PPO is less efficient. For larger concentrations of PPO, the time constant increases again as self-absorption processes in PPO start playing a role. Studies of the efficiency of the energy transfer and its dependence on the time constants are on-going. Further details will be given in [7].

To further characterize the mixtures, emission spectra of the scintillator samples have been measured where two excitation methods have been used: excitation by ultraviolet light and by electrons of $\sim 10$ keV. For the second method, a device [8] has been used consisting of a small electron accelerator with a thin exit window. This 300 nm silicon-nitride window allows the electrons to escape from the electron gun vacuum with only $\sim 10\%$ energy loss. Both excitation methods result in the same scintillation spectra. This leads us to the conclusion that there is no dependence of the spectra on the excitation mechanism.

4. Physics potential
One of the main goals of the project is the search for proton decay. Monte Carlo calculations have shown [9] that a unique sensitivity to the proton decay channel $p \rightarrow K^+\bar{\nu}$ is obtained in a liquid-scintillator detector. For this decay mode, which is favored by some Supersymmetry theories, a sensitivity for the proton lifetime $\tau > 4 \cdot \times 10^{34}$ y at 90% C.L. after 10 y measuring time has been derived. This value gives an order of magnitude improvement with respect to the current best limit which has been achieved by the Superkamiokande detector [10].

In case of a supernova explosion, LENA will provide valuable information on spectra and fluxes of the arriving neutrinos. Especially $\bar{\nu}_e$ will be measured with high accuracy due to the large cross section for the reaction $\bar{\nu}_e p \rightarrow ne^+$. For an 8 M$_\odot$ supernova exploding in the center of our galaxy (10 kpc distance) a signal of $\sim 15,000$ events is expected. Recently, a study of the neutrino rates for different supernova models and for different oscillation scenarios (including possible values of $\theta_{13}$ and $\nu$-mass hierarchy) has been performed [11]. It is shown that separation of different explosion models is possible due to the detection via the neutral current reaction on $^{12}$C which is not affected by neutrino oscillations.

Even in the absence of a galactic supernova, core-collapse explosion mechanisms can be investigated by detecting the diffuse background of supernova neutrinos from explosions that happened throughout the history of the Universe. As all flavours of neutrinos and antineutrinos are produced, $\bar{\nu}_e$ can be used to measure this neutrino background by their capture on protons. In our calculations it has been shown [12], that within 10 y of exposure, various supernova models can be discriminated and information on the supernova rate in the near Universe can be gained which is closely linked to the star formation rate.
The LENA detector will be capable to detect solar neutrinos via neutrino electron scattering. Due to the high statistics on $^7$Be neutrinos ($\sim 5400$ events/day), time fluctuations, e.g. the day-night counting asymmetry which is caused by Earth matter effects, could be studied. The experience gained with the Borexino experiment [2] will significantly help to recognize and discriminate various types of background events. If the $^{11}$C cosmogenic background can be successfully identified, neutrinos from the pep reaction and from the CNO cycle could be detected. Spectroscopy in this 1-2 MeV region will allow to look at the solar matter effect resonance and eventually to search for non-standard interactions [13].

KamLAND has shown [14] that $\nu_e$ from beta decay of radioactive elements inside the Earth can be tagged. For LENA at a location in an already existing mine close to Pyhäsalmi (Finland) [16] about 1000 events per year are expected [15]. Decays from Uranium and Thorium could be separated as the produced neutrinos have different characteristic energy spectra.

In addition, neutrino oscillation parameters could be studied with LENA. For a location close to power reactors, a good sensitivity to $\theta_{12}$ has been predicted [17]. Furthermore, the possibility to use LENA for a beta beam experiment is being investigated.

5. Summary and Outlook

A large liquid-scintillation detector of the scale of 50 kt constitutes a unique tool for neutrino astrophysics, geophysics and elementary particle physics. The good energy resolution, low energy threshold and high light yield make it a good choice for a future observatory.

Recently, LENA has joined the European initiative LAGUNA [18] (Large Apparatus for Grand Unification and Neutrino Astrophysics). In this framework, three different detector technologies with common physics interests are being studied: A 500 kt water Cherenkov detector, MEMPHYS (MEgaton Mass PHYSics) [19], a 100 kt liquid Argon device, GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment) [20] and the already described 50 kt liquid scintillator, LENA. Not only the physics potential but also common technical requirements as well as questions concerning possible underground locations are discussed within a European context.

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