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Future neutrino physics with LENA (Low Energy Neutrino Astronomy)

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Abstract. The proposed large-volume detector LENA (Low Energy Neutrino Astronomy) is a multi-purpose liquid-scintillator experiment. Its sensitive mass of 50 kt allows for high-statistic measurements of astrophysical and terrestrial low-energy neutrino sources. Moreover, new limits might be put on the lifetime of the proton decay channel into $K^+\bar{\nu}$.

1. Introduction
Taking advantage of the high potential of liquid-scintillator detectors (LSDs), the proposed LENA detector [1] hopes to follow in the footsteps of the Borexino [2] and KamLAND [3] experiments. LSDs feature low-energy threshold, good energy resolution, particle identification, and efficient background discrimination. Therefore and due to its large mass, LENA is sensitive to many different low-energy neutrino sources. Furthermore, the test for baryon number violation manifesting in the proton decay, is a major focus of the experiment.

2. Detector design
A sketch of the detector layout can be seen in Figure 1. It is divided into several subvolumes in order to get a well-shielded and radiopure fiducial target volume required for low-energy measurements.

The inner detector, containing the organic liquid scintillator, is enclosed by a cylindrical hollow-core conrete tank with a height of 100 m and 32 m diameter. A support structure for the optical modules (OMs) is erected at about 1m distance from the inner tank walls. Basically, an OM is composed of a photo multiplier (PMT), a light concentrator, and a pressure encapsulation with an acrylic window filled with mineral oil. Using 12" PMTs and light concentrators with an area increase factor of 1.75, roughly 29,600 PMTs are needed to obtain 30% optical coverage. The support scaffolding is separated from the active volume by an optical shield, at 2 m distance from the concrete wall. Equivalent structures are installed both at the bottom and the top of the detector. Thus, the cylinder defining the active volume contains 59,082 m^3, corresponding to 50.8 kt of LAB. The tank is surrounded by a water Čerenkov muon veto with a minimum width of 2 m and equipped with about 4,000 8" PMTs, also shielding against radioactive decay

Figure 1. Artistic view of the LENA detector. The diameter of the conrete tank is 32m and the height 100m. The liquid scintillator, coloured in yellow, is monitored by $\sim$ 29,600 optical modules with 12" PMTs mounted on a steel scaffolding. The space between tank and detector cavern is filled with water and serves as a muon veto and additional shielding against external radiation.

products from the rock and against neutrons induced by undetected muons in the surrounding rock. In order to tag muons even more efficiently, limited streamer tubes are placed on top of the tank. Since muons and their induced reactions within the detector volume are a severe background for low-energy physics, LENA has to be built in an underground facility with at least 4.000 m.w.e. shielding.

In the EU-funded LAGUNA (Large Apparatus studying Grand Unification and Neutrino Astrophysics) FP-7 study, several sites in Europa have been investigated concerning their ability to host future large volume detectors. Besides LENA, a liquid-Argon TPC (GLACIER) [4] and a Čerenkov detector (MEMPHYS) [5] are under consideration. Concerning LENA, only the Pyhäsalmi mine, Finland, and the Fréjus site in France fulfil the shielding requirement. In the follow-up study LAGUNA-LBNO (Long-Baseline Neutrino Oscillations), the focus is directed towards LENA as a far detector of a long-baseline neutrino beam experiment.

Several different mixtures of solvents (i.e. LAB, PXE) and solutes (PPO, bis-MSB) at different concentrations have been investigated within the LENA project. Showing outstanding properties concerning light yield, attenuation length, and α-β discrimination and a sufficiently fast decay time, LAB+ 2 g/ℓ PPO+ 20 mg/ℓ bis-MSB is the most promising scintillator candidate. Other parameters such as electron and proton quenching, emission spectra, pulse shape discrimination power, and wavelength-dependent index of refraction are investigated as well (see [1] for an overview).

3. Physics goals

3.1. Galactic Supernova Neutrinos

A core-collapse supernova (SN) within the Milky Way or in its close vicinity will trigger a huge signal in such a big detector as LENA. A variety of different flavour-sensitive interaction channels opens the possibility to determine detailed time-resolved neutrino 'light curves' and to do spectroscopy. Both information on the SN explosion mechanism and on neutrino properties can be obtained from such an observation.

The neutrino emission of a core-collapse SN can be divided into three parts. During the neutronization burst, mainly ν_e are emitted for about 10 ms. This robust feature is largely independent from the progenitor mass and the equation of state. In LENA, one expects about 100 events via ν–p and ν–e scattering. In the accretion phase ($\sim$100 ms), neutrinos of all flavours are emitted. The hierachy of their mean energies is most distinct: $\langle E_{\nu_e}\rangle < \langle E_{\overline{\nu}_e}\rangle < \langle E_{\nu_x}\rangle$, where ν_x stands for $\nu_\mu, \nu_\tau, \overline{\nu}_\mu$, and $\overline{\nu}_\tau$. Consequently, this phase is most suited for the search for flavour oscillations. The cooling phase lasts for about 10-20 s, emitting all flavours with thermal spectra. The luminosity is estimated to be equipartioned and the hierachy less pronounced. The total expected event rates for this last phase for a $8M_\odot$ progenitor star in a distance of 10 kpc ranges between 10,000-20,000 [1]. More than 10,000 events alone can be observed in the inverse beta decay channel, allowing for a finely time-resolved measurement.

3.2. Diffuse SN neutrinos

The neutrinos from the diffuse Supernova background (DSNB), originating from core collapse Sne throughout the history of the Universe, provides another way to measure SN neutrinos. In contrast to a single galactic SN burst, they provide information on the average $\overline{\nu}_e$ spectrum. The large cross section of the inverse beta decay and its clear coincidence signal enable its discrimination against background and allow to search even for the small DSNB flux. In the observation window between 10 and 30 MeV, constrained by the irreducibe reactor and atmospheric anti-neutrino background, about 35-70 events can be observed in 10 years [6]. This allows for spectoscopy and to test SN models and variations in emission. A severe background comes from NC interactions from atmospheric νs, knocking out a neutron from ^{12}C and mimicking the delayed coincidence signature. Preliminary MC studies show that this background is up to 20 times higher than the DSNB signal. Tagging of the residual ^{11}C and pulse shape analysis may however help to reach a signal-to-background ratio greater than unity.

3.3. Solar Neutrinos

Due to its huge mass and low energy threshold, LENA is able to reach unprecedented statistics in solar neutrinos. This would allow to do precise determinations of the SSM neutrino flux and MSW oscillation parameters. Like in Borexino, the main detection channel is neutrino-electron scattering. The huge statistics in ^{7}Be–ν, about 10^4 counts per day in 35 kton fiducial mass, enables to search for temporal fluctuations in the solar ν flux. It has been shown that there is a 3σ discovery potential for amplitudes as low as 0.5% for frequencies between 10 minutes and 100 years [7].

3.4. Geoneutrinos

Geoneutrinos are $\overline{\nu}_e$ from the decay chains of ^{238}U and ^{232}Th, and the decay of ^{40}K abundant in the Earth's mantle and crust. While part of the $\overline{\nu}_e$ from the decay chain of Uranium and Thorium can be detected via the inverse beta decay, the neutrinos from the Potassium decay are invisible as the beta endpoint is below the energy threshold of 1.8 MeV. Due to the large number of protons and the large cross section, LENA can yield unprecedented statistics with $\sim$ 1000 geoneutrino events in one year [1]. Thus, the error one the total geoneutrino flux can be determined within few percent. This will help to understand the radiogenic contribution to the total heat flux of the Earth and the abundances of ^{238}U and ^{232}Th, and reveal information on geophysical processes and origin and formation of the Earth.

3.5. Short-baseline Neutrino Oscillations

Artificial neutrino sources like nuclear power plants or accelerator beams can be used to determine neutrino mixing parameters like the mass square differences, the neutrino mixing angles, or the CP violating phase.

An analysis for the Fréjus site [8] showed that thanks to the huge statistics, LENA could be used as a precision measurement of the solar mixing parameters Δm^2_{12} and θ_{12}. After a single year of data taking, the 3σ error of Δm^2_{12} could be pushed below 3%.

Neutrino oscillometry is a recently proposed possibility to access θ_{13}, Δm^2_{13}, and sterile neutrinos. Placing a monoenergetic EC source ($\sim$ 100 keV) close to the detector, the idea is to continuously monitor the neutrino flavour disapperance within the detector. Current calculations performed for MCi sources of ^{51}Cr and ^{57}Se show a great discovery potential especially concerning sterile neutrinos [9]. Since the neutrinos are low-energetic and detected via elastic ν–e scattering, solar neutrinos will pose an irreducible background, putting constraints on the minimum source strength.

3.6. Indirect Dark Matter Search

As proposed by [10], LENA can also be used for the search for $\overline{\nu}_e$ from dark matter annihilation or decay. In regions with high DM densities, i.e. galaxy centers, DM particles can annihilate or decay efficiently producing an observable flux of neutrinos or other SM particles. Taking advantage of the clear inverse beta decay signal, the good energy resolution, background reduction and large size of LENA, distict monoenergetic peaks can be observed or strong constraints put on the DM particle lifetime or annihilation cross section, respectively.

3.7. Proton Decay

Due to its huge mass and the large number of protons, LENA offers the possibility to search for baryon number violations. Especially the minimal SUSY SU(5)-favoured proton decay into a Kaon and a neutrino is easily accessible. While the Kaon is invisible to water Čerenkov detecors, the coincidence of the Kaon and the muon from its decay gives a clear signal in LENA. After 10 years of non-observation, the current Super-K limit [11] can be improved by one order of magnitude to $\tau > 4 \cdot 10^{34}$ years at 90%C.L. [12]. With a rise time cut, background from atmospheric ν_μ can be rejected with an efficiency of at least 10^{-5}, retaining a proton decay detection efficieny of 65%. Rejecting background from atmospheric ν_μ by a rise time cut, retains a detection efficiency for proton decay of 65%. Other proton decay modes such as the SUSY SO(10)-favoured $p \to \pi^0 + e^+$ decay require event topology reconstruction and have to be studied further in detail.

3.8. GeV Event Reconstruction

Especially high-energy events in LENA, e.g. from long-baseline GeV neutrino beams, can have complex topologies. In order to reconstruct both single and multi-particle events, a Monte Carlo simulation has been set up investigating angular and energy resolution. With the help of a logarithmic likelihood fit to the charge distribution and first hit times from photons arriving at each PMT, track parameters can be deduced at high precision. It takes advantage of the non-sphericity of the light emission of high-energy particle tracks. For example, the obtained angular resolution for 300 MeV single muons is in the order of few degrees.

4. Conclusions

The great variety of different applications in several physics fields shows the large potential of the liquid scintillator detector LENA. While the LSD technique has already been proven succesfully, a further increase of mass greatly improves the sensitivity in many aspects. Moreover, the energy range from sub-MeV to GeV covered by LENA is unrivalled.

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