Proton decay in the large liquid scintillator detector LENA: study of the background

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Abstract. Using Geant4 Monte-Carlo simulations the potential of the Low Energy Neutrino Astronomy (LENA) liquid scintillator detector for the investigation of a possible proton decay within the channel \( p \rightarrow K^+\nu \) is discussed. Special emphasis is given to the study of background events.

1. Introduction
The best current experimental limits for the proton lifetime \( \tau \) are obtained by Super-Kamiokande [1] with \( \tau > 5.4 \cdot 10^{33} \) y and \( \tau > 2.3 \cdot 10^{33} \) y for the decay modes \( p \rightarrow e^+\pi^0 \) and \( p \rightarrow K^+\nu \) respectively. The experimental proton-lifetime limit concerning \( p \rightarrow e^+\pi^0 \) is already two orders of magnitude bigger than that predicted by Grand Unified Theories (\( \sim 10^{31} \) y). Supersymmetry theories predict the decay channel \( p \rightarrow K^+\nu \) as the dominant one with a lifetime \( \tau \sim (0.33 - 3) \cdot 10^{34} \) y [2]. In this case the experimental limit is still one order of magnitude smaller than the theoretical prediction. That motivates the search for proton decay into this mode.

As a possibility to further improve the proton-lifetime sensitivity the construction of a large (50 kt) liquid scintillator detector LENA, has been proposed [3, 4]. The LENA detector is the perfect device not only for the search for proton decay but also to investigate low energy neutrinos in a wide variety of physics fields, from astrophysics, e. g., measurements of solar, supernovae and supernova relic neutrinos, to geophysics and the study of neutrino properties.

2. Detector
The LENA detector is planned as a cylinder of about 100 m length and 30 m diameter. An inside part of 13 m radius will contain approximately 50 kt of liquid scintillator while the outside part will be filled with water to act as a muon veto. A fiducial volume for proton decay will be defined having a radius of 12 m. Covering about 30% of the surface, 12 000 photomultipliers of 50 cm diameter each will collect the light produced by the scintillator. PXE (phenyl-o-xylylethane) will be used as scintillator solvent. From measurements in the Counting Test Facility (CTF)

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for BOREXINO at the Gran Sasso underground laboratory [5] can be concluded that after purification, PXE can reach an attenuation length of $\sim 12$ m and a photoelectron yield of $\sim 120$ pe/MeV.

3. Proton decay

3.1. Event topology

In LENA, proton decay events via the mode $p \rightarrow K^+\nu$ have a very clear signature. The kaon causes a prompt monoenergetic signal ($T=105$ MeV) and from the kaon decay there is a short-delayed second monoenergetic signal, bigger than the first one. The kaon has a lifetime of $\tau(K^+) = 12.8$ ns and two main decay channels: with a probability of 63.43 % it decays via $K^+ \rightarrow \mu^+\nu_\mu$ and with 21.13 %, via $K^+ \rightarrow \pi^+\pi^0$. In the first case, the muon causes a short-delayed monoenergetic signal ($T=152$ MeV) and after $\tau(\mu^+) = 2.2 \mu$s, also the muon will decay: $\mu^+ \rightarrow e^+\nu_e\pi^-\nu_\mu$, the $e^+$ producing a third long-delayed signal. In the second case, the short-delayed monoenergetic signal comes from the electromagnetic shower due to the gammas from the $\pi^0$ decay (246 MeV), the kinetic energy of the $\pi^+$ (108 MeV) and the $\mu^+$ of its decay ($\pi^+ \rightarrow \mu^+\nu_\mu$, $\tau(\pi^+) = 26$ ns). Again, there will be a third long-delayed signal from the succeeding decay $\mu^+ \rightarrow e^+\nu_e\pi^-\nu_\mu$.

The event structure just explained is valid only for free protons. However, in this investigation, protons from the $^{12}$C in the scintillator have also been included [4]. For these events, further nuclear effects have to be considered, e.g. Fermi motion and binding energy, because they modify the energy of the kaon.

3.2. Background events

The main background source are muon neutrinos $\nu_\mu$ produced by cosmic ray interactions in the atmosphere. These atmospheric $\nu_\mu$ can interact with the scintillator producing muons in the energy range where the search for the proton decay is performed. The rate of these events in the relevant energy range can be derived from the Super-Kamiokande measurements [6]. From this data we find an event rate of: $\Gamma \sim 4.8 \cdot 10^{-2}$ (MeV$^{-1}$kt$^{-1}$y$^{-1}$) where the LENA energy window as well as the volume have to be introduced in MeV and kt, respectively. A Monte Carlo simulation based on Geant4 [7] has been performed [8] to estimate a possible background rejection by pulse shape analysis using the risetime of the signal because of the clear signature of proton decay events. By comparing the time intervals in the risetime of proton decay and background signals, a reduction factor of $2 \cdot 10^4$ results with an efficiency in the risetime cut of $\varepsilon_T = 0.65$. In the analysis performed an energy window of 500 MeV has been taken leading to an efficiency in the energy cut of $\varepsilon_E = 0.995$.

Atmospheric neutrinos can interact with the detector producing also hadrons. The most probable reactions are the single pion production [9] and different strange particles production [10]:

\begin{align*}
\nu_\mu + p &\rightarrow \mu^- + \pi^+ + p' \\
\nu_\mu + p &\rightarrow \mu^- + K^+ + p \\
\nu_\mu + n &\rightarrow \mu^- + K^+ + \Lambda^0 \\
\nu_\mu + n &\rightarrow \mu^- + K^+ + \Lambda^0 + \pi^0
\end{align*}

Simulations of these reactions have also been performed. The signal of reactions 1, 3 and 4 do not show the same signature as the proton decay signal. Reaction 2 can be responsible for a potential background for proton decay in the LENA detector. For this case, only neutrinos with energies between 650 and 900 MeV can produce a signal with a signature similar to that of the proton decay. The flux of these neutrinos amounts to $\sim 10\%$ of the total atmospheric neutrino.
flux. Within this energy window a rate of 0.8 events per year \( (y^{-1}) \) caused by such neutrino reactions is predicted. To distinguish these background reactions from proton decay events the number of delayed electrons produced will be taken into account.

For proton decay in the channel considered, always one and only one positron is produced by the decay of the kaon. In the background reaction always one electron and one positron are present, one from the \( \mu^- \) decay and another from the \( K^+ \) decay chain. Using this argument the number of events of the type of reaction 2 expected in the LENA detector is 0.064 \( y^{-1} \).

Combining the different background events studied, the estimated background rate for proton decay in LENA through the channel \( p \rightarrow K^+\nu \) is \( \sim 1 \ y^{-1} \).

3.3. Sensitivity

After applying the time cut and the energy cut, one can calculate the final efficiency \( \varepsilon = \varepsilon_E \cdot \varepsilon_T \) of the proton-decay detection in the channel considered. The activity for the proton decay is given by the expression:

\[
A = \varepsilon N_p t_m / \tau
\]

where \( \varepsilon = 0.65; \ N_p = 1.45 \cdot 10^{34} \) is the number of protons in the detector; \( t_m \) is the measuring time and \( \tau \) is the lifetime of the proton. For the current proton lifetime limit for the channel considered (\( \tau = 2.3 \cdot 10^{33} \) y) [1], about 40.7 proton decay events would be observed in LENA after a measuring time of ten years with about 1 background event. If no signal is seen in the detector within this ten years, the lower limit for the lifetime of the proton will be increased to \( \tau > 4 \cdot 10^{34} \) y at 90% C.L. If one candidate is observed, the lower limit will be reduced to \( \tau > 3 \cdot 10^{34} \) y at 90% C.L. with a 32% probability of this event being background.

4. Conclusions

An efficiency of \( \sim 65\% \) for the search for proton decay in the LENA detector and a background rate of about 1 event per year have been determined. A lower limit for the proton lifetime of \( \tau > 4 \cdot 10^{34} \) y (at 90% C.L.) can be reached if no proton decay event is measured within ten years. That is an order of magnitude better than the Super-Kamiokande limit.

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