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# Monte Carlo Study of the Fast Neutron Background in LENA

Diploma Thesis

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#### Abstract

LENA (Low Energy Neutrino Astronomy) is a proposed next generation liquid-scintillator detector with about 50 kt target mass.

Its main physics goals are the detection of solar neutrinos, supernova neutrinos, geoneutrinos and the search for proton decay. Besides the direct observation of a supernova, LENA will also search for the so called diffuse supernova neutrino background (DSNB) that was generated by core-collapse supernovae throughout the universe. Up to now the DSNB has not been detected, due to the low flux. As only 6 to 13 DSNB events per year are expected in LENA, background is a crucial issue for DSNB detection.

Due to the delayed coincidence signal from the inverse beta decay detection channel, liquid-scintillator detectors offer a high background-discrimination efficiency. One remaining background source are fast neutrons that are produced by muons in the surrounding rock and propagate into the detector unnoticed, as these events mimic the same delayed coincidence signal. Atmospheric neutrinos generate also neutrons by neutral current reactions on carbon in the scintillator.

Therefore, a Monte Carlo simulation of neutron production in the rock and of the propagation into the detector was performed to determine the fast neutron background rates. Subsequently, possible methods for the identification of fast neutron events were analyzed. As typical neutron interactions produce pulse shapes different from positrons that are emitted in inverse beta decay reactions, neutron events can be identified by pulse shape analysis. Thus, an experiment was performed to investigate the efficiency of pulse shape discrimination in a small liquid-scintillator sample. The obtained results of the discrimination efficiency and pulse shape parameters were used as input parameters for the Monte Carlo Simulation of the LENA detector. Based on this, the efficiency for neutron- $\bar{\nu}_e$  discrimination was analyzed for the largescale geometry of LENA. The neutron rejection efficiency was determined to over 99.4% in PXE and over 99.0% in LAB, making a detection of the DSNB with a signal to background ratio of about 10:1 or better achievable with both PXE and LAB in LENA.

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# Chapter 1

## Introduction

The neutrino was postulated in the 1930s by Wolfgang Pauli in order to conserve energy, momentum, and spin for the  $\beta$  decay [1]. Neutrinos interact only weakly, therefore they are not affected by electromagnetic fields and point directly back to their source, like photons do. But unlike electromagnetically interacting photons they are only marginally affected by matter. Therefore, neutrino astronomy provides a unique way to look inside many astrophysical objects and phenomena, like core-collapse supernovae, the Sun, or the Earth itself [2].

The proposed LENA (Low Energy Neutrino Astronomy) detector is, due to its large target of ~ 50 kt, capable of performing high-statistic measurements of strong astrophysical neutrino sources as well as detecting rare neutrino events, like geoneutrinos (see Section 2.2.4) or diffuse supernova background neutrinos (see Section 2.2.3). As only 6 to 13 DSNB events per year are expected in LENA, background identification is crucial for its detection. One background source are fast neutrons, because they mimic the signature of  $\bar{\nu}_e$  events. They are produced by cosmic muons in the surrounding rock of the detector and propagate into the detector unnoticed. Therefore, the fast neutron background rate in LENA as well as techniques for its suppression were analyzed in this thesis.

In the present Chapter a short introduction about neutrino physics in and beyond the Standard Model of particle physics will be given. Furthermore, a brief overview about Water-Čerenkov and liquid-scintillator neutrino detectors will be given. The experimental setup and the physics programm of the proposed LENA (Low Energy Neutrino Astronomy) detector will be outlined in the second Chapter. In Chapter 3, the results of a Monte Carlo Simulation of the fast neutron background in LENA will be presented. The results of a measurement of the pulse shape discrimination efficiency of neutron and gamma events in a small liquid-scintillator detector will be presented

Doublets	Singlets
$\left(\begin{array}{c} e_L \\ \nu_{e,L} \end{array}\right) \left(\begin{array}{c} \mu_L \\ \nu_{\mu,L} \end{array}\right) \left(\begin{array}{c} \tau_L \\ \nu_{\tau,L} \end{array}\right)$	$e_R  \mu_R  \tau_R$

Table 1.1: Leptons in the scope of the weak interaction.

in Chapter 4. Subsequently, the efficiency of pulse shape discrimination of neutron and  $\bar{\nu}_e$  events in LENA is determined by a Monte Carlo simulation in Chapter 5. Based on the resulting neutron rejection efficiency, the cosmogenic background remaining for the DSNB detection will be analyzed in Chapter 6.

### 1.1 Neutrinos in the Standard Model

In the Standard Model (SM) of particle physics, leptons and quarks are divided into three generations [3]. Each generation consists of one charged lepton (e,  $\mu$ ,  $\tau$ ), one corresponding neutrino ( $\nu_e$ ,  $\nu_{\mu}$ ,  $\nu_{\tau}$ ) and 2 quarks. For every particle of the SM there exists one antiparticle, with the same mass and liftime but opposite quantum numbers. The left-handed eigenstates of the charged leptons and their counterparting neutrino form doublets under the weak interaction, while the right-handed eigenstates of the charged leptons are described as singlets (see Table 1.1) [4]. Neutrinos are generated only in left-handed states and since the helicity is conserved (because neutrinos are massless) they stay left-handed. Thus, right-handed neutrinos do not exist in the standard model. Neutrinos only interact through the weak interaction. Parity is maximally violated in the weak interaction as the  $W^{\pm}$  and  $Z^{0}$  vector bosons couple only to left-handed particles and right-handed antiparticles [5]. The lepton flavour number is conserved in the Standard Modell, in the sense that in every reaction the number of leptons from one generation must be constant [3]. Therefore, charged current (CC) reactions can only occur within one lepton doublet.

While the coupling constants of the weak interaction are comparable in strength to the coupling constant of the electromagnetic interaction, the fact that the exchange bosons are massive ( $m_{W^{\pm}} = 80 \text{ GeV}, m_{Z^0} = 91 \text{ GeV}$ ) severely reduces the strength and range of the weak interaction for low energies [4].

Neutrinos with energies in the range of some MeV have consequently cross sections in the order of  $10^{-43}$  cm<sup>2</sup> to  $10^{-44}$  cm<sup>2</sup>, resulting in a mean free path  $\lambda_{\nu} \approx 10^{18}$  m  $\approx 100$  light yrs in normal stellar matter with  $\rho \approx 1 \frac{g}{\text{cm}^3}$ [3].

### 1.2 Neutrinos beyond the Standard Model

Contrary to the predictions of the SM, there are several evidences from solar neutrino experiments [6, 7], that there is a mixture between mass and flavour eigenstates as it is present in the quark sector, and that the neutrinos are not massless.

#### **1.2.1** Vacuum Neutrino Oscillations

The weak flavour eigenstates of the neutrino  $(\nu_e, \nu_\mu, \nu_\tau)$  can be expressed as linear superpositions of orthogonal neutrino mass eigenstates  $(\nu_1, \nu_2, \nu_3)$  [8]:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
(1.1)

U is the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. It can be parameterized with three rotation angles  $\theta_{ij}$  and one CP violating phase  $\delta$  [9]:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
(1.2)

In this parameterization  $s_{ij}$  and  $c_{ij}$  are abbreviations of  $sin(\theta_{ij})$  and  $cos(\theta_{ij})$ . The time evolution of the neutrino mass eigenstates is given by the Schrödinger equation<sup>1</sup>:

$$|\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle \tag{1.3}$$

where  $E_i$  is the energy of the mass eigenstate  $\nu_i$ .

Assuming that the neutrino has a finite but small mass, such that  $m_i \ll p_i$ and  $p_i \approx E$ , the neutrino energy  $E_i$  can be written as :

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \simeq E + \frac{m_i^2}{2E}$$
 (1.4)

From equations (1.1)-(1.4) it follows that the probability  $P_{\alpha \to \beta}$  to detect a neutrino in the flavour eigenstate  $\beta$ , which was produced in the flavour eigenstate  $\alpha$ , is:

$$P_{\alpha \to \beta} = \left| \langle \nu_{\beta} | v_{\alpha}(t) \rangle \right|^{2}, \text{ with } \left| \nu_{\alpha} \right\rangle = \sum_{i} U_{\alpha i} \left| \nu_{i}(t) \right\rangle$$
(1.5)

<sup>&</sup>lt;sup>1</sup>In the following  $\hbar = c = 1$ 

$\Delta m_{12}^2 = (7.59 \pm 0.20) \cdot 10^{-5} \mathrm{eV}^2$
$ \Delta m_{23}^2  = (2.43 \pm 0.13) \cdot 10^{-3} \text{eV}^2$
$\sin^2\left(2\theta_{12}\right) = 0.87 \pm 0.03$
$\sin^2(2\theta_{23}) > 0.92$
$\sin^2(2\theta_{13}) < 0.19$

Table 1.2: Neutrino square mass differences and mixing angles [4].

$$P_{\alpha \to \beta} = \left| \sum_{i} U_{\alpha i}^* U_{\beta i} e^{-\frac{m_i^2 t}{2E}} \right|^2 \tag{1.6}$$

If one takes the simplified approach of only two neutrino flavours, the PMNS matrix can be parameterized with one rotation angle  $\theta$  and the oscillation probability can be written as:

$$P_{\alpha \to \beta} = \sin^2(2\theta) \sin^2\left(\frac{m_2^2 - m_1^2}{4E}L\right) \tag{1.7}$$

The neutrino only oscillates if the masses  $m_i$  of the mass eigenstates are not equal and if  $\theta > 0$ , which implies that U is not diagonal. Consequently the lepton flavour number is not conserved in the case of neutrino oscillations, contrary to the prediction of the SM. Up to now the mixing angles  $\theta_{12}$  and  $\theta_{23}$ and the mass square differences  $\Delta m_{12}^2$  and  $|\Delta m_{23}^2|$  were measured in several experiments (see Table 1.2). For the mixing angle  $\theta_{13}$  only upper limits could be determined. The best limit was achieved with  $\sin(2\theta_{13}) < 0.19$ by the CHOOZ experiment [10]. While the sign of  $\Delta m_{12}^2$  is known from solar neutrino experiments [6, 7], the sign of  $\Delta m_{23}^2$  is still undetermined. Therefore, there are two possible hierachies of the neutrino mass eigenvalues, the normal  $(m_3 > m_2 > m_1)$  and the inverted hierachy  $(m_2 > m_1 > m_3)$ .

#### 1.2.2 The Mikheyev-Smirnov-Wolfenstein Effect

When neutrinos propagate through matter, they can scatter off electrons and nucleons. While the electron neutrino can interact both through NC and CC reactions with electrons, the muon and tau neutrinos can only interact via NC reactions at low energies  $(E(\nu_{\mu}) < m_{\mu}, E(\nu_{\tau}) < m_{\tau})$ .

This leads to an additional potential  $A = 2\sqrt{2G_F N_e p}$  for the  $\nu_e$ , where  $G_F$  is the weak Fermi constant,  $N_e$  the electron density of the matter passed and p the neutrino momentum. This potential can be interpreted as an addition



Figure 1.1: The MSW effect in the Sun [9]. Electron neutrinos are produced in the solar center at high electron densities in the matter eigenstate  $\nu_{2,m}$ . When the adiabatic condition (the density gradient being small in comparison to the matter oscillation length) is fulfilled, the  $\nu_e$  leaves the Sun in the vacuum eigenstate  $\nu_2$ , which has a great contribution to  $\nu_{\mu}$ .

to the mass terms in the Hamiltonian, that describes the propagation of the neutrino mass eigenstates.

The vacuum mixing angle  $\theta$  (in the following, the simplified approach of only two neutrino flavours is taken again) is replaced by the matter mixing angle  $\theta_m$  [9]

$$\sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{\left(\cos(2\theta) - \frac{A}{\Delta m^2}\right)^2 + \sin^2(2\theta)}$$
(1.8)

From equation (1.8) follows that at a critical density  $\rho_c$ , where  $\cos(2\theta) = \frac{A}{\Delta m^2}$ ,  $\sin^2(2\theta_m)$  equals 1, independently of the vacuum mixing angle. For electron neutrinos that are produced in the center of the Sun, a resonant conversion into  $\nu_{\mu,\tau}$  occurs if they are generated at a higher electron density  $n_e$  than the resonant density  $n_{e,res}$  (see Figure 1.1), the so called Mikheev-Smirnov-Wolfenstein (MSW) effect [8]. As the resonant density  $n_{e,res}$  depends on the neutrino energy, the MSW effect applies to the high-energetic neutrinos of the solar spectrum (see Figure 1.2).

A  $\nu_e$  that is generated in the center of the Sun, is produced only in the matter eigenstate  $\nu_{2,m}$ , because  $\theta_m$  is close to 90°, due to the high density. When the neutrino traverses the Sun, the density decreases until the critical density is reached.

If the density gradient is small in comparison to the oscillation length, an adiabatic conversion occurs where the neutrino stays in the mass eigenstate  $\nu_{2,m}$ . After the neutrino leaves the Sun, it remains in the mass eigenstate  $\nu_2$  as it propagates to the earth.

The probability to detect an electron neutrino is constant as no vacuum oscillations occur:

$$P_{ee} = \sin^2(2\theta_{12}) \cong 30\% \tag{1.9}$$

While the lower part of the solar neutrino spectrum, like the pp and <sup>7</sup>Be neutrinos, is subject vacuum oscillations only, the high-energetic part of the <sup>8</sup>B spectrum is subject to the MSW effect (see Figure 1.2).



Figure 1.2: The survival probability of  $\nu_e$  from the Sun. The survival probability according to the MSW effect (assuming a large mixing angle  $\sin(2\theta_{13}) \approx 0.2$ ) is shown in black. Additionally, the measurements from BOREXINO (<sup>7</sup>Be neutrinos), SNO (<sup>8</sup>B neutrinos), and the prediction for the pp solar neutrinos is shown.

## **1.3** Real-time Neutrino Detectors

The first detection of solar neutrinos was achieved in the Homestake experiment by Raymond Davis in the 1970s [11]. The detection reaction was

$$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$$
 (1.10)

where the produced <sup>37</sup>Ar nuclei had to be extracted from the <sup>37</sup>Cl and counted. With this technique, only a time- and energy-integrated measurement of the solar neutrino flux was possible. Furthermore, this experiment

was only sensitive to  $\nu_e$ , while electron antineutrinos, muon, and tau neutrinos could not be detected. After the Homestake experiment new neutrino detectors were developed, which were able to measure the energy of a neutrino in real-time. The first neutrino detectors of this type were Water-Čerenkov detectors (WCDs), which are capable of measuring the direction of the incoming neutrino, but are only sensitive to the higher energetic solar neutrinos [7] (see Section 1.3.1). Later on, large-volume liquid-scintillator detectors (LSDs) also provided the possibility to perform real-time measurements of the neutrino flux. LSDs can not provide information on the direction of the neutrino, but have a much lower threshold than WCDs and can thus measure a large part of the solar spectrum [12] (see Section 1.3.2).

#### **1.3.1** Water-Čerenkov Detectors



Figure 1.3: Cerenkov light emission of a particle moving faster than the speed of light in a medium  $\left(\frac{c}{n}\right)$ . The interference of the spherical light waves emitted along the particle track generates the characteristic conical shape of the light front [13].

If a charged particle moves faster than the speed of light in a medium  $(\frac{c}{n})$ , it emits Čerenkov light. Due to the constructive interference of spherical light waves emitted along the particle track, a conical front is generated analogously to a supersonic mach cone (see Figure 1.3) [13]. The opening

angle  $\alpha$  of the cone depends on the velocity  $\beta = \frac{v}{c}$  of the charged particle and the refractive index n of the medium

$$\cos \alpha = \frac{1}{\beta n} \tag{1.11}$$

From equation (1.11) follows that the maximum opening angle is given by  $\alpha_{max} = \arccos(\frac{1}{n})$ . To generate Čerenkov light, the particle velocity must be greater than  $\frac{c}{n}$ . The threshold energy is therefore

$$E_t = \gamma m_o = \frac{1}{\sqrt{1 - n^{-2}}} m_0 \tag{1.12}$$

For water n = 1.33 and thus  $E_{w,t} = 1.52m_0$  and  $\alpha_{w,max} = 41.4^{\circ}$ .

The Cerenkov light yield in water is in the range of approximately 200 photons per MeV [12]. These photons can be detected with photomultiplier tubes (PMTs). The direction of the light-emitting particle can be reconstructed from the orientation of the Čerenkov cone. Due to the low light yield, the detection threshold is usually in the order of several MeV [14, 7].

#### KamiokaNDE/Super-Kamiokande

The KamiokaNDE detector [14] was the first experiment that could measure solar neutrinos in real time. Originally constructed for the search for nucleon decay, it was also sensitive to neutrinos. It was shielded by 1000 m rock (2700 m.w.e. depth) against cosmic muons. The target mass consisted of 2.1 kt pure water, monitored by 948 PMTs.

The detection reaction was elastic scattering from neutrinos off electrons. After the neutrino scattered off the electron, the Čerenkov light of the electron was detected. Due to the high threshold of 7.5 MeV, only <sup>8</sup>B-neutrinos could be detected [14]. The direction of the recoil electron is correlated with the direction of the incident neutrino. This can be used for background suppression, as the recoil electron tracks of solar neutrinos always point away from the Sun.

KamiokaNDE was replaced in 1996 by Super-Kamiokande [7]. Super-Kamiokande has a 22.5 kt fiducial mass of ultrapure water, observed by 11146 PMTs. The threshold could be lowered to 5 MeV, but Super-Kamiokande is still only sensitive to <sup>8</sup>B-neutrinos (see Figure 2.4). After 1496 days of data taking, the measured flux for the <sup>8</sup>B-neutrinos is [7]

$$\Phi_{^8B} = (2.35 \pm 0.02[stat.] \pm 0.08[syst.]) \cdot 10^6 \text{cm}^{-2} \text{s}^{-1}$$
(1.13)

This flux only accounts to approximately 47% of the flux predicted by the Standard Solar Model (SSM) [7]. As Super-Kamiokande is (due to the higher

cross section of CC reactions) predominantely sensitive to electron neutrinos, the difference between the predicted and the measured flux can be explained by neutrino oscillations (see Section 1.2).

#### **SNO**

The solar neutrino experiment SNO (Sudbury Neutrino Observatory) used 1 kt heavy water  $(D_2O)$  as a target [6]. The detector is covered by 2 km rock, corresponding to 6 km w.e. shielding against cosmic muons. SNO uses three detection reactions:

• Elastic scattering off electrons (ES)

$$\nu + e^- \to \nu + e^- \tag{1.14}$$

Electron neutrinos can interact via charged current (CC) and neutral current (NC) reactions, muon and tau neutrinos only via NC reactions. The cross-section for  $\nu_e$  is therefore about a factor of 6.6 higher than for  $\nu_{\mu,\tau}$ .

• Deuteron dissociation

$$CC: \qquad \nu_e + D \rightarrow e^- + 2p \qquad (1.15)$$

$$NC: \qquad \nu + D \quad \to \nu + n + p \tag{1.16}$$

The charged current reaction (1.15) is only sensitive to electron neutrinos and gives the opportunity to measure the  $\nu_e$ -flux alone. The neutral current reaction 1.16 is sensitive to all neutrino flavours, and contrary to reaction 1.14 every flavour has the same cross section. Hence, it is a measure for the total neutrino flux.

The threshold of SNO was 5.5 MeV and the measured fluxes were [6]:

$$\Phi_{CC} = 1.72^{+0.05}_{-0.05}(stat.)^{+0.11}_{-0.11}(syst.) \cdot 10^{6} \text{cm}^{-2} \text{s}^{-1}$$
(1.17)

$$\Phi_{ES} = 2.34^{+0.23}_{-0.23}(stat.)^{+0.15}_{-0.14}(syst.) \cdot 10^{6} \text{cm}^{-2} \text{s}^{-1}$$
(1.18)

$$\Phi_{NC} = 4.81^{+0.19}_{-0.19}(stat.)^{+0.28}_{-0.27}(syst.) \cdot 10^{6} \text{cm}^{-2} \text{s}^{-1}$$
(1.19)

The result for  $\Phi_{NC}$  is in good agreement with the predictions from the Standard Solar Model [6]. The survival probability for electron neutrinos  $\frac{\Phi_{CC}}{\Phi_{NC}}$  is determined to approximately 36%, which is due to the MSW effect in the Sun. As muon and tau neutrinos also contribute to  $\Phi_{ES}$ , the flux is greater than  $\Phi_{CC}$ , but lower than  $\Phi_{NC}$ , due to the reduced cross-sections for muon and tau neutrinos of reaction (1.14).

#### **1.3.2** Liquid-Scintillator Detectors

A liquid scintillator consists of at least two components. An organic solvent that serves as target material and a solute at low concentration, the so-called wavelength shifter. Both consist of aromatic molecules. When a charged particle moves through the solvent, the weakly bound electrons in the  $\pi$ orbitals of the benzene rings get excited or ionized. A solvent molecule in an excited state can subsequently transfer its energy non-radiatively to another solvent or solute molecule. Finally, a photon is emitted through deexcitation of a solute molecule. This photon has a larger wavelength than a photon directly emitted by the solvent. As organic solvents become more transparent at longer wavelength, the shifted light can travel further distances through the detector. Like in a WCD the light is detected by PMTs, that cover the walls of the detector. Another advantage of the wavelength shifter is that the wavelength of the emitted photons can be adjusted to the region where common PMTs are most efficient [12].

The photons are emitted isotropically and within a few nanoseconds [15]. Hence, using the photon arrival time and the hit pattern of the PMTs, the position of the event vertex inside the detector volume can be reconstructed, but the directional information is usually lost.

The light yield of a scintillator depends on the incident particle. Heavier particles like protons and  $\alpha$ -particles have a greater energy loss per unit path length than lighter particles like electrons and muons. As a result, after an event involving a heavy particle, the density of molecules in an excitated state along the particle track is larger than in the case of light particle. Thus, the reaction

$$S^* + S^* \to S^+ + S_0 + e^-$$
 (1.20)

is more likely to happen, where  $S^*$  denotes an excitated molecule,  $S^+$  an ionized molecule and  $S_0$  is a molecule in ground state. Therefore less energy is converted into light, as the ionized molecule does not generate scintillation light [15]. The ratio of deposited to visible energy is described by the quenching factor. For  $\alpha$  particles, quenching factors of more than 10 relative to electron events can be reached in common scintillators [16].

The great advantage of liquid-scintillator detectors (LSD) is that the light yield is with ~  $10^4$  scintillation photons per MeV [15] much greater than the light yield of WCDs (200 photons per MeV). Thus, the energy resolution is better and the detection threshold is much lower. In contrast to that, the isotropic emission of the scintillation light allows no reconstruction of the particle direction at low energies. Information on the incident particle's direction can only be gained for high-energetic events like cosmic muons or atmospheric neutrinos [17]. Depending on the neutrino flavour, there are several possible detection reactions in a liquid-scintillator detector. The most important ones are elastic scattering off electrons (see reaction (1.14)) and the inverse beta decay channel for  $\bar{\nu}_e$ :

$$\bar{\nu}_e + p \to n + e^+, \qquad n + p \to d + \gamma (2.2 \,\mathrm{MeV})$$
(1.21)

The elastic scattering reaction has in principle no threshold. The actual threshold of the detector is governed by intrinsic radioactive contaminants. As <sup>14</sup>C is naturally abundant in organic scintillators, a neutrino detection at energies below the end point of the <sup>14</sup>C  $\beta$ -spectrum of 156 keV is not possible. The inverse beta decay reaction has a threshold of 1.8 MeV. It provides a delayed coincidence signal as the positron gives a prompt signal and the neutron is captured after ~ 200  $\mu$ s on a free proton [18]. A WCD is also sensitive to this reaction, but the 2.2 MeV  $\gamma$  from the neutron capture is below the detection threshold. Therefore, the background suppression for  $\bar{\nu}_e$  detection is much better in a LSD.





Figure 1.4: The BOREXINO detector [19]. It consist of 270 t liquid scintillator in the Inner Vessel, that is shielded by several layers of buffer liquid and water. The scintillation light is detected by 2212 PMTs.

BOREXINO is a solar neutrino experiment that is also sensitive to geo- $\bar{\nu}_e$  and reactor- $\bar{\nu}_e$ . It uses 280t of liquid scintillator as a target. The scintillator

mixture consist of pseudocumene (PC, 1,2,4-trimethylbenzene), used as the solvent, and  $1.5\frac{g}{1}$  PPO (2,5-diphenyloxazole) as wavelength shifter. The scintillator is contained in a transparent nylon membrane with a radius of 4.25 m and a thickness of  $125 \,\mu\text{m}$ , the so-called Inner Vessel (IV) (see Figure 1.4).

The Inner Vessel is surrounded by a buffer liquid, contained in the Outer Vessel (OV), with a radius of 5.5 m. It shields the Inner Vessel from external radioactivity. The buffer liquid is composed of PC and  $3\frac{g}{1}$  DMP (dimethyl-phytalate). It has nearly the same density as the scintillator in the IV, therefore buoyancy forces on the IV are reduced. The DMP quenches the scintillation yield of PC by a factor of ~ 20. Therefore, almost no scintillation is generated in the buffer.

The OV serves as a barrier to Radon diffusion and is placed in a Stainless Steel Sphere (SSS), with a radius of 6.85 m. The space between the OV and the SSS is also filled with buffer liquid. 2212 PMTs are mounted to the SSS, corresponding to an optical coverage of 30% of the surface.

The SSS is placed in a steel dome of 18 m diameter, 16.9 m height, which is filled with 2.1 kt of deionized water. The outside of the SSS and the floor of the Outer Detector (OD) are equipped with 208 PMTs in total. The OD serves as an active muon veto. Muons traversing the OD produce Čerenkov light, which is detected by the PMTs.

BOREXINO is taking data since 2007 [20]. Due to the low radioactive background level achieved, it could perform the first real time detection of <sup>7</sup>Be neutrinos. BOREXINO measured an event rate of [21]

$$49 \pm 3(stat.) \pm 4(syst.) \frac{\text{counts}}{\text{day} \cdot 100\text{t}}$$
(1.22)

corresponding to a flux of

$$\Phi_{^{7}\text{Be}} = (5.08 \pm 0.25) \cdot 10^{9} \text{cm}^{-2} \text{s}^{-1}$$
(1.23)

The results are in good agreement with the predictions from the SSM taking neutrino oscillations into account.

## Chapter 2

## The LENA Project

LENA (Low Energy Neutrino Astronomy) has been proposed as a next generation large volume liquid-scintillator detector [2]. Its target mass is with  $\sim$ 50 kt considerably larger than the target mass of the present liquid-scintillator detectors (BOREXINO: 300 t, KAMLAND: 1000 t). This allows on the one hand high-statistic measurements of strong astrophysical neutrino sources like the Sun, and on the other hand the detection of rare events, such as geoneutrinos (see Section 2.2.4) or diffuse supernova background neutrinos (see Section 2.2.3).

The LENA Project is currently in a design phase as a part of the LAGUNA (Large Apparatus for Grand Unification and Neutrino Astrophysics) collaboration, that shall last until the end of 2010 [12] at least.

## 2.1 Detector Design

#### 2.1.1 Detector Layout

Figure 2.1 shows a schematic overview of the current LENA design, according to a pre-design study for the Pyhäsalmi location [22].

The detector consists of a 100 m high vertical steel cylinder with 30 m in diameter that is placed in a 115 m high cavern. A vertical design is favorable for the construction of the steel cylinder. The cavern is elliptically shaped with 50 m maximum diameter in order to minimize rock mechanical risk [22]. The steel tank is filled with liquid scintillator. Inside the steel cylinder, the volume is divided by a thin Nylon Vessel into the buffer volume shielding external radioactivity and the target volume of 13 m diameter and 100 m height, corresponding to  $5.3 \cdot 10^4 \text{m}^3$ . At the moment the composition of the liquid scintillator is not decided, PXE (phenyl-xylyl-ethane) and LAB (lin-



Figure 2.1: Schematical view of the LENA detector [22]. The target volume consists of 50 kt of liquid scintillator. It is surrounded by 2 m of nonscintillating buffer liquid. 13500 PMTs detecting the scintillation light are placed on the inner surface of the steel cylinder, which contains the target and buffer volume. The surrounding 2 m of water also serve as passive shielding and as an active Water-Čerenkov muon veto. Plastic scintillators on top of the detector complete the active muon veto. ear akylbenzene) are considered as solvents and PPO (2,5-diphenyloxazole), bisMSB (1,4-bis-(o-methylstrylyl)-benzene) and PMP (1-phenyl-3-mesityl-2-pyrazoline) as wavelength shifters [15]. Depending on the exact composition, the target mass ranges from 45-53 kt. The buffer volume is filled with an in-active liquid, which should have a similar density as the scintillator in order to minimize buoyancy forces on the Nylon Vessel.

An optical coverage of 30% would require 13500 photomultiplier tubes (PMTs) with a photocathode diameter of 20 inch. Reflective light-concentrators mounted on the PMTs can reduce the number or size of the PMTs necessary to achieve the aspired optical coverage. The effect of these concentrators on the detector performance is due to be analyzed in Monte Carlo simulations. The space between the steel tank and the cavern walls is filled with water (at least 2 m), which shields the inner detector from external radiation coming from the rock and from muon-induced neutrons. Additionally, it functions as a Water-Čerenkov Detector, which tags muons that are passing the detector. If a muon crosses the water target it produces Čerenkov light, which is detected by 1500 PMTs. Another benefit from the water is that the rock pressure is reduced and the forces on the tank generated by the scintillator are compensated.

On top of the steel tank, plastic scintillator panels are mounted, which serve also as an active muon veto.

#### 2.1.2 Detector Location

The physics goals (see Section 2.2) require at least 3500 m.w.e. shielding for LENA. Another important aspect is a low  $\bar{\nu}_e$  flux from nuclear power plants (NPPs) as it is a background for the geoneutrino and DSNB detection (see Section 2.2.3 and 2.2.4). Within the LAGUNA [23] design study, several locations in Europe have been discussed. The three sites that feature the necessary depth are:

- **CUPP**: The Center for Underground Physics in Pyhäsalmi is located in the middle of Finland. LENA can be built at 1440 m depth (4000 m.w.e.) connected to the Pyhäsalmi Mine. Due to the large distance to the central european NPPs the reactor neutrino background is with a flux of  $1.9 \cdot 10^5$  cm<sup>-2</sup>s<sup>-1</sup> low, which is favorable for geoneutrino and DSNB detection.
- LSM: The Laboratoire Souterraine de Modane (France) is connected to a highway tunnel between Italy and France in the Alps. The shielding corresponds to  $\sim 4000$  m.w.e. depth. Several French NPPs are located

within 100 km distance, the reactor neutrino background is with a flux of  $1.6 \cdot 10^6 \text{cm}^{-2} \text{s}^{-1}$  approximately one order of magnitude larger than at the CUPP.

• Sunlab: The Sieroszowice Underground Laboratory (Poland) is located near Wrocław. The original plan was to use inactive shafts of a salt mine in 950 m depth, but recently an investigation of a deeper location below the salt body has begun. A possible location for LENA at a depth corresponding to 3600 m.w.e. shielding has been found. Due to the small thickness of the rock layer there, only a horizontal version of LENA is possible at this site.

## 2.2 Physics Goals

#### 2.2.1 Solar Neutrinos

In the Sun, energy is produced by nuclear fusion of hydrogen to helium in two different reaction sequences, the pp-chain (Figure 2.2) and the CNO-cycle (Figure 2.3). In the pp-chain, helium is produced directly through the fusion of hydrogen, while in the CNO cycle <sup>12</sup>C serves as a catalyst. The CNO-cycle is further divided into four sub-cycles, with the CNO-I cycle being the most important of the four for the energy production in the Sun.

While the pp-chain is dominating in the Sun and contributes to 98% of its energy production, the CNO-cycle becomes dominant in larger stars of multiple solar masses. Both reaction mechanisms release 26.73 MeV energy in total and result in the same net reaction

$$4p \to {}^{4}\mathrm{He} + 2e^{+} + 2\nu_{e} \tag{2.1}$$

Neutrinos from different reactions have different energies. The calculated neutrino spectrum of the Sun according to the Standard Solar Model (SSM) [26] is shown in Figure 2.4.

The detection threshold in LENA will be only limited by the radioactive contamination. If the same level of radiopurity as present in BOREXINO was achieved, a detection threshold of 250 keV should be possible.

Table 2.1 shows the expected event rates for the elastic  $\nu - e$  scattering channel, using two different solar model predictions and assuming a conversative fiducial volume of 18 kt [12].

Approximately 25 pp- $\nu$  events per day are expected above 250 keV. This rate is probably not high enough to distinguish the neutrino events from the natural <sup>14</sup>C background. With ~ 5000 events per day, the <sup>7</sup>Be -  $\nu$  flux can



Figure 2.2: The single reactions of the pp-chain [24]. There are 4 reactions that generate neutrinos. The neutrinos from the pp and hep reaction have a continious energy spectrum, while the neutrinos from the <sup>7</sup>Be and pep reaction are monoenergetic due to the kinematics of the reaction.



Figure 2.3: The CNO-I-cycle and CNO-II-cycle[25]. There are three reactions generating neutrinos with a continious energy spectrum:  $^{13}N$  (CNO-I), $^{15}O$  (CNO-I and CNO-II) and  $^{17}F$  (CNO-II)



Figure 2.4: Neutrino spectrum calculated according to the SSM [26]. The neutrino fluxes resulting from the pp-chain reactions are plotted as black solid lines, the fluxes from the CNO-cycle reactions as dashed blue lines.

be measured with a high precision, if the background levels are comparable to BOREXINO. One year of measuring time should be sufficient to identify count rate modulations of 1.5% [27]. This allows the measurement of seasonal variations of the solar neutrino flux (6.9%) due to the excentricity of the Earth orbit. Density and temperature changes in the core of the Sun that cause variations in the neutrino production rate could be measured for the first time.

The  ${}^{8}\text{B} - \nu$  flux can be measured with a threshold of 2-2.8 MeV [27]. As cosmogenic  ${}^{10}\text{C}$  provides a background for the  ${}^{8}\text{B}$ -neutrino detection between 2 MeV and 2.8 MeV, the exact threshold will depend on the efficiency of  ${}^{10}\text{C}$  background rejection and on the level of  ${}^{208}\text{Tl}$  contamination. With the 2.8 MeV threshold, the MSW-LMA solution for the  $\nu_{e}$  survival probability (see Figure 1.2) could be proved with 99.5% C.L., after 2 years data taking [27].

The detection of the CNO/pep- $\nu$  fluxes depends on the level of cosmogenic <sup>11</sup>C background. <sup>11</sup>C is produced in spallation reactions on <sup>12</sup>C by high energetic muons that cross the detector. Therefore, the <sup>11</sup>C background depends on the rock shielding. If LENA is build at the intended depth of 4000 m.w.e. the CNO/pep- $\nu$  signal to background ratio would be 1:5 [12]. A reduction of the <sup>11</sup>C background is possible with the Three-fold Coincidence technique. This method is based on the correlation in space and time between the crossing muon, the spallated neutron and the decay of the <sup>11</sup>C nuclide

Source	Event Rate $[d^{-1}]$		
	BPS08(GS)	BPS08(AGS)	
pp	$24.92\pm0.15$	$25.21\pm0.13$	
pep	$365 \pm 4$	$375 \pm 4$	
hep	$0.16\pm0.02$	$0.17\pm0.03$	
<sup>7</sup> Be	$4894 \pm 297$	$4460\pm268$	
<sup>8</sup> B	$82 \pm 9$	$65 \pm 7$	
CNO	$545 \pm 87$	$350\pm52$	

Table 2.1: Solar neutrino event rates in LENA, assuming 18kt fiducial volume and 250 keV detection threshold, for high (BPS08(GS)) and low (BPS08(AGS)) solar metallicity [12].

[28]. At the moment the theoretical uncertainty of the CNO flux is with 30% quite large. A high statistic measurement of this flux could provide information on the solar metallicity and test the accuracy of the current solar models.

A measurement of the pep- $\nu$  flux could be used for a test of the  $\nu_e$  survival probability in the energy region between 1 and 2 MeV, where the transition between matter-induced to vacuum oscillations is predicted by the MSW-LMA solution. It also gives informations about the pp-flux, because the rate for the pep reaction is proportional to that for the pp reaction [25].

#### 2.2.2 Supernova Neutrinos

Stars with masses greater than 8 solar masses ( $M_{\odot}$ ) build up a shell structure with an iron core in the centre towards the end of their lifes [30]. With increasing density of the iron core, the gravitational pressure becomes higher than the Fermi-pressure of the electrons and the core collapses until it reaches nuclear density, where the collapse is stopped by the Fermi pressure of the neutrons that are formed by the reaction (2.2). Further collapsing material now bounces on the ultra-dense core and builds an outward running shock front.

A supernova explosion releases ~ 99% of its energy through neutrinos. In the first 20 ms of the supernova explosion  $\nu_e$  are created by the reaction

$$e^- + p \to n + \nu_e \tag{2.2}$$

the so-called neutronisation burst. After that the core cools down through emission of  $\nu \bar{\nu}$  pairs of all flavours [30].

Detection Channel	Event Rate
(1) $\bar{\nu}_e + p \rightarrow n + e^+$	7500-13800
(2) $\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$	150-610
(3) $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$	200-690
(4) $\nu_e + {}^{13}\mathrm{C} \to {}^{13}\mathrm{N} + e^-$	$\sim 10$
(5) $\nu + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu$	680-2070
$(6) \ \nu + e^- \to e^- + \nu$	680
(7) $\nu + p \rightarrow p + \nu$	1500-5700
(8) $\nu + {}^{13}\mathrm{C} \to {}^{13}\mathrm{C}^* + \nu$	$\sim 10$
total	10000 - 20000

Table 2.2: Expected event rates for a supernova explosion of a  $8 M_{\odot}$  star in the center of our galaxy (d=8 kpc). The uncertainty in the event rates comes from different supernova explosion models and neutrino oscillation scenarios [29].

About one to three supernova explosions are expected in our galaxy per century. If a 8  $M_{\odot}$  star explodes in the center of our galaxy (10 kPc distance), 10000-20000 neutrino events are expected in LENA. Table 2.2 shows the predicted event rates of a supernova explosion in the center of our galaxy in LENA, for the different detection channels. While the first four channels are charged current (CC) reactions and allow a separate measurement of  $\nu_e$  and  $\bar{\nu}_e$ events, the last 4 channels are neutral current (NC) reactions and measure the sum of all flavours. The NC-channels are therefore not affected by neutrino oscillations and depend only on the supernova model. With the inverse beta decay channel (1) the  $\bar{\nu}_e$  spectrum and the temporal evolution of the  $\bar{\nu}_e$ -flux can be studied. The transit of  $\bar{\nu}_e$ 's through the matter of the progenitor star envelope or of the Earth leaves an imprint on the  $\bar{\nu}_e$  spectrum. The survival probability of the electron and antielectron neutrinos depends on the neutrino mass hierarchy and, amongst others, on the unknown mixing angle  $\theta_{13}$  [29]. Thus, a measurement of the  $\bar{\nu}_e$  and  $\nu_e$  spectrum gives information about the mixing angle  $\theta_{13}$  and the neutrino mass hierarchy.

About 74  $\nu_e$ -events from the neutronisation burst are expected in LENA [29]. A measurement of the neutronisation burst would give valuable information about the details of the core-collapse process.

#### 2.2.3 Diffuse Supernova Neutrino Background

Core-collapse supernovae explosions throughout the universe have generated a cosmic neutrino background, the so called diffuse supernova neutrino background (DSNB). It contains information about the core-collapse supernova explosion mechanism itself, about the supernova rate (SNR) and about the star formation rate up to high redshifts of  $z \simeq 5$  [18]. The predicted flux is with  $\sim 10^2 \,\mathrm{cm}^{-2}\mathrm{s}^{-1}$  about 8 orders of magnitudes smaller than the solar neutrino flux [18]. Up to now the DSNB could not be detected. The Super-Kamiokande experiment provides the best limit of  $1.2 \,\bar{\nu}_e \,\mathrm{cm}^{-2}\mathrm{s}^{-1}$  for energies above 19.3 MeV [31].

As all neutrino and antineutrino flavours are produced in a supernova explosion, the inverse beta decay channel, which has a low threshold (1.8 MeV) and the largest cross section at low energies, can be used for the detection of the DSNB:

$$\bar{\nu}_e + p \to n + e^+ \tag{2.3}$$

The neutron is much heavier than the positron, therefore the positron gets almost all the energy of the  $\bar{\nu}_e$ , but reduced by ~ 1.8 MeV, due to the Q-Value of reaction (2.3). However, the annihilation of the positron adds  $2 \,\mathrm{m}_e c^2$  to the signal, thus leading to a total reduction of 0.8 MeV. While the positron gives a prompt signal, the neutron is captured by free protons after ~ 200  $\mu$ s:

$$n + p \rightarrow d + \gamma \left(2.2 \,\mathrm{MeV}\right)$$
 (2.4)

The 2.2 MeV  $\gamma$  gives a delayed coincidence signal, therefore DSNB events can be seperated from radioactive background events. While the threshold of Water-Čerenkov detectors lies above 2.2 MeV, liquid scintillator detectors like LENA can easily detect the delayed coincidence signal from the neutron capture on a free proton.

Reactor and atmospheric  $\bar{\nu}_e$  give an indistinguishable background to the DSNB signal. The background from reactor  $\bar{\nu}_e$  sets a lower limit for the DSNB search at  $E(\bar{\nu}_e) \sim 10 \text{ MeV}$ , the exact limit depends on the detector site. Figure 2.5 shows the reactor  $\bar{\nu}_e$  spectrum at various sites compared to the expected DSNB spectrum.

Atmospheric  $\bar{\nu}_e$  exceed the DSNB signal at about 25 MeV, thus defining an upper limit. Therefore, a window between approximately 10 MeV and 25 MeV is left for the DSNB detection (see Figure 2.6). Exact values depend on the detector site.

In this energy region 6 to 13 events will be detected in LENA per year. Insitu produced <sup>9</sup>Li, muon-induced fast neutrons and neutral current reactions from atmospheric neutrinos provide an additional background. A detailed analysis of this background and the consequences for the DSNB detection will be given in Chapter 6.



Figure 2.5: Reactor  $\bar{\nu}_e$  spectra at Frejus, Pyhäsalmi and Hawaii. The shaded regions show model and experimental uncertainties. For comparison, the DSNB spectrum according to the supernova simulations performed by Keil, Raffelt and Janka (KRJ) [32] is shown.

Provided that ~ 100 events will be detected after 10 years of measuring time, information about the supernova spectrum can be obtained with a spectroscopical analysis of theses events. The DSNB spectrum depends on the emitted neutrino spectrum by a core-collapse supernova and on the redshiftdependent supernova rate. Although it is not possible to measure both from the DSNB spectrum alone [35], the progress in optical observations of the supernova rate and the star formation rate, which is linked to it, could soon provide accurate input values for the DSNB. In this case, the mean energy of the supernova spectrum could be determined on a uncertainty level of  $\pm 10\%$  $(1\sigma)$  [12].

#### 2.2.4 Geoneutrinos

Antineutrinos from  $\beta^-$  decays of radioactive isotopes in the Earth, like <sup>238</sup>U, <sup>232</sup>Th and their daughter nuclides as well as <sup>40</sup>K, generate a  $\bar{\nu}_e$ -flux, the socalled geoneutrinos. The present models of the Earth assume that ~ 50% of the terrestial heat flow is generated by radiocative decays [36]. Geoneutrinos from the uranium and thorium chains can be detected in a liquid-scintillator detector through the inverse beta decay reaction (2.3). A measurement of  $\bar{\nu}_e$ from potassium is not possible, due to the 1.8 MeV threshold for the detection



Figure 2.6: Expected event rates of DSNB  $\bar{\nu}_e$  for LENA in Pyhäsalmi according to the supernova simulations performed by the Lawrence Livermore Group (LL) [33], by Keil, Raffelt, and Janka (KRJ) [32], and by Thompson, Burrows, and Pinto (TBP) [34]. The reactor  $\bar{\nu}_e$ , atmospheric  $\bar{\nu}_e$ , and the Super-Kamiokande limit are also shown. The shaded region represents the possible DSNB  $\bar{\nu}_e$  event range due to uncertainties of the Supernova rate.

channel (see Figure 2.7). The predicted event rate depends on the detector site, as the amount of radioactive isotopes differs between the continental and the oceanic crust [37]. In LENA,  $\sim 1000$  events per year are expected if it is built at the currently favoured site in Pyhäsalmi (Finland) [37].



Figure 2.7: Predicted  $\bar{\nu}_e$  spectrum of  $\beta^-$  decays from the <sup>238</sup>U and <sup>232</sup>Th chains as well as <sup>40</sup>K [38]. The 1.8 MeV threshold of the inverse beta decay channel is also shown. Due to this threshold, only antineutrinos that are generated by the <sup>238</sup>U and <sup>232</sup>Th chains can be detected.

The largest background for the geoneutrino detection are reactor  $\bar{\nu}_e$ . At the Pyhäsalmi site about 240 events per year from reactor  $\bar{\nu}_e$  are expected in the relevant energy window from 1.8 MeV to 3.2 MeV. The reactor  $\bar{\nu}_e$ spectrum below 8 MeV is well known. Therefore, this background can be calculated using the  $\bar{\nu}_e$  events above 3.2 MeV and statistically subtracted in the geoneutrino region. Another background is due to radioactive impurities.  $\alpha$  particles, emitted for example by <sup>210</sup>Po, produce neutrons through the reaction

$${}^{13}\mathrm{C} + \alpha \to {}^{16}\mathrm{O} + n \tag{2.5}$$

These neutrons give a prompt signal by scattering off protons and a delayed signal due to the capture on a free proton, thus mimicing the signature of a geoneutrino. If the radiopurity level of BOREXINO was reached in LENA, this background would account to  $\sim 10$  events per year [37]. Another background source are fast neutrons that are generated by cosmic muons in the rock surrounding the detector and propagate into the detector. A detailed analysis of this background will be presented in Chapter 3.

With an expected rate of ~  $1000 \bar{\nu}_e$  events per year, a very accurate measurement of the combined geoneutrino flux originating from crust and mantle could be done. However, a second detector at an oceanic location would be needed to disentangle the contributions and in this way to distinguish between different Earth models.

#### 2.2.5 Proton Decay

In the standard model of particle physics, the Baryon number is conserved, and therefore the proton is stable. But there is actually no fundamental gauge symmetry, which generates the Baryon number conservation (as there is e.g. for the charge conservation) [39]. In the most important extensions of the standard model, the Bayron number is not conserved, predicting a decay of the proton [39].

In the past, there have been great efforts to measure the proton lifetime, but up to now only limits could be determined. The best limits were achieved by the Super-Kamiokande experiment. For the channel  $p \to e^+\pi^0$  the limit is  $\tau_p > 8 \cdot 10^{33}$  y [40]. Supersymmetric models predict proton decay via the channel  $p \to K^+ \bar{\nu}$  [39]. The present limit for this channel is  $\tau_p > 2 \cdot 10^{33}$  y [41]. While in a Water-Čerenkov detector like Super-Kamiokande the  $K^+$ is not visible due to the Čerenkov threshold, in a liquid-scintillator detector like LENA both the  $K^+$  and its decay products are detected, thus leading to a clear double-peak signal. Therefore, a better sensitivity can be reached. The main background to this channel arises from charge current reactions of atmospheric neutrinos in the energy range of several 100 MeV. This background can efficiently be reduced to less than one count in 10 years using pulse shape analysis [15]. If no signal was seen in 10 years data taking, the proton lifetime limit could be increased to  $\tau_p > 4 \cdot 10^{34}$  y, about one order of magnitude better than the current limit [15].

#### 2.2.6 Dark Matter Annihilation Neutrinos

There is evidence from cosmology and astrophysics for the existence of dark matter (DM). The most prominent are galactic rotation curves, gravitational lensing, large scale structures and the cosmic microwave background (CMB) [43].

While many DM candidates with masses in the GeV region have been proposed, there are also models that predict a lower mass in the MeV region for the DM particle [44]. If the DM particle is a Majorana particle, it can annihilate via the reaction  $\chi\chi \to \nu\bar{\nu}$ . Antielectron neutrinos produced in the annihilation process could be identified in LENA via the inverse beta decay



Figure 2.8: Expected signal of DM annihilation neutrinos in LENA, after 10 years data taking for two different values of the DM mass,  $m_{\chi} = 20 \text{ MeV}$  and  $m_{\chi} = 60 \text{ MeV}$ . The dashed lines show the contribution from reactor antineutrinos, atmospheric antineutrinos and the DSNB. The solid lines show the sum spectra including the dark matter signal [42]. Note the sharp peak at  $E_{\text{vis}} \sim 20 \text{ MeV}$  for  $m_{\chi} = 20 \text{ MeV}$ , and the broad peak at  $E_{\text{vis}} \sim 55 \text{ MeV}$  for  $m_{\chi} = 60 \text{ MeV}$ .

reaction. Reactor  $\bar{\nu}_e$ , atmospheric  $\bar{\nu}_e$  and the DSNB provide an indistinguishable background, resulting in a observational window between 10 MeV and 100 MeV. The expected signal from DM annihilation and background sources after 10 years of data taking is shown in Figure 2.8. With a positive signal, the mass of the DM particle and its cross section at DM freeze-out in the early universe could be measured [42].

## Chapter 3

# Monte Carlo Simulations of the Fast Neutron Background in LENA

Cosmic muons that pass the LENA detector can produce fast neutrons. The energy spectrum of the muon-induced neutrons extends to the GeV region. These neutrons have therefore a large range, and it is possible that a neutron reaches the Inner Vessel (IV) of LENA without triggering the muon veto, as the energy of the scattered protons is usually below the Čerenkov threshold. In the IV the neutron can give a prompt signal due to scattering off protons and a delayed signal caused by the neutron capture on a free proton. Thus, a fast neutron entering the detector from outside gives the same delayed coincidence signal as the inverse beta decay reaction (see equation (1.21)). Muon-induced neutrons therefore provide a background for  $\bar{\nu}_e$  detection in LENA, especially for the detection of rare events like the DSNB.

In this chapter, the results of a GEANT4-based Monte-Carlo simulation of this background will be presented.

In a first step, the neutron production by cosmic muons was simulated (see Section 3.4). The resulting energy spectrum and angular distribution were used as an input for the second simulation, where the propagation of the neutrons into the LENA detector was simulated (see Section 3.5). Furthermore, possible methods to identify neutron events were analyzed (see Section 3.7).

### **3.1** Neutron Production Processes

At large underground depths, the mean muon energy is about 200 - 300 GeV (see Figure 3.1) [45]). At this energy, there are three dominant processes for



Figure 3.1: The mean muon energy, depending on the depth [45].

the muon-induced neutron production:

- A muon interacts via a virtual photon with a nucleus, producing a nuclear disintegration and thus neutrons (see Figure 3.2).
- The muon produces a electromagnetic cascade. In this cascade, high energetic photons can cause spallation reactions.
- The incident muon induces a hadronic cascade. The generated Hadrons  $(\pi^{\pm}, K^{\pm}, K^{0}, n, p)$  can also cause spallation reactions [45]. Additionally, a  $\pi^{-}$  can be absorbed by a nucleus. The nucleus then deexcites, amongst others, through neutron emission. As the  $\pi^{-}$  is only absorbed at low energies, the neutron energy of this process is cut off at  $E_{max} = m_{\pi^{-}} m_{b}(n)$  (e.g.  $E_{max}(^{12}C) \approx 120 \text{ MeV}$ ), where  $m_{b}(n)$  is the binding energy from the neutron in the nucleus.



Figure 3.2: The Feynman diagram of a muon spallation process [46].

## 3.2 The GEANT4 Simulation Toolkit

GEANT4 is a software toolkit that simulates the interactions of particles with matter. It is written in C++ and follows the object-orientated design approach [47]. This design allows the user to customize GEANT4 for his specific needs.

First of all, the user has to define the detector. GEANT4 uses the concept of "logical" and "physical volumes". A logical volume consist of a "solid", that describes the geometry of the detector element. The logical volume is then defined through a solid and a material. Materials are dynamically defined by the user. In a first step, the necessary elements are created and in a second step the material is defined by its elemental composition. The physical volume then defines the orientation of the logical volume.

It is also possible to define a sensitive detector for a logical volume. When a particle makes a physical interaction in this logical volume, a so-called "hit" is generated. A hit stores information about the interaction, for example position, time and energy deposition.

After the definition of the detector geometry, the physics list for the simulation has to be specified. A physics list consist of the particles that should be known to the simulation and the physical processes for the particles, like elastic scattering, inelastic scattering etc. A detailed description of the physics models that are used in GEANT4 can be found in [48].

Every event starts with one or more primary particles. The primary and secondary particles are propagated through several steps that form a track. The step length depends on the registered processes and the detector geometry. Each active process has a defined step length, depending on its interaction. The smallest of these step lengths is taken as the physical step length. After that the geometrical step length is calculated as the distance to the next volume boundary. The actual step length then is the minimum of the physical and geometrical step length, so that each step is within one logical volume.

After the step length is calculated, all active continuous processes, e.g. bremsstrahlung or ionisation energy loss, are invoked. The particle's kinetic energy is only updated after all invoked processes have been completed. If the track was not terminated by a continuous process, the track properties, like kinetic energy, position and time, are updated. Afterwards the discrete processes, e.g. elastic scattering or positron annihilation, are invoked. The track properties are updated again and the secondary particles that were produced in this step are stored.

The primary particles and all produced secondary particles are tracked until they have either stopped inside or have left the detector volume.

## 3.3 Simulation Setup

The present simulation program is based on the GEANT4 simulation toolkit (Version 4.9.2.p01) and was originally written by T. Marrodàn Undagoitia [15], further developed by J. Winter [29] and customized by the author.

#### 3.3.1 Detector Setup

The target volume of the simulated LENA detector is a 100 m high cylinder with 26 m in diameter. It is surrounded by the 2 m thick buffer volume. Either phenyl-xylyl-ethane (PXE,  $C_{16}H_{18}$ ) or linear alkylbenzene (LAB,  $C_{18}H_{30}$ ) could be used as a material for the buffer and the target volume. The buffer and the target volume are contained in a 4 cm thick stainless steel cylinder, which is surrounded by a 2 m thick water mantle, serving as the muon veto. The muon veto is surrounded by limestone rock (CaC0<sub>3</sub>) with 2.73  $\frac{g}{cm^3}$  density (see Figure 3.3).



Figure 3.3: Detector geometry of the simulation. The muon veto (2 m thickness, 100 m height) is plotted in blue, the buffer volume (2 m thickness, 100 m height) in yellow and the target volume (26 m diameter, 100 m height) in red. The buffer volume and the muon veto are divided by a 4 cm thick stainless steel tank.

Instead of simulating 13500 PMTs mounted to the stainless steel tank as sensitive detectors, the whole cylinder containing the organic liquids is treated
as a sensitive detector to speed up the simulation. A common liquid scintillator has a light yield of ~ 10000 photons per MeV. The optical coverage in LENA is 30% and the quantum efficiency of a standard PMT is 20% [12]. As the optical coverage and the quantum efficiency is 100% in the simulation, the light yield was reduced to  $0.3 \cdot 0.2 \cdot 10000 = 600$  photons per MeV to compensate for the better detection efficiency. For the buffer region the scintillation process was deactivated, as the buffer volume should be filled with a nonscintillating liquid (see Section 2.1.1).

The predefined GEANT4 physics list QGSP\_BERT\_HP (including the G4Mu-NuclearInteraction and the G4MuonMinusCaptureAtRest process) was used (for details see [48]). This list was chosen, as it includes several models to simulate hadronic interactions over a broad range of energies. Thus, it is possible to simulate low energetic neutrons below 1 MeV as well as high energetic neutrons above 1 GeV. Additionally, the interactions between high energetic (E > 3 GeV) gamma quanta and nuclei are included, which are necessary for the simulation of the neutron production. A validation of the used models can be found in [49] and [50]. As QGSP\_BERT\_HP does not include the scintillation process, an own model for the scintillation had to be implemented and added to the physics list.

### 3.3.2 Scintillation and Light Propagation

The scintillation model that is implemented in the simulation uses two exponential functions to describe the probability density function (PDF) F(t) of the photon emission process:

$$F(t) = \frac{N_f}{\tau_f} e^{-\frac{t}{\tau_f}} + \frac{N_s}{\tau_s} e^{-\frac{t}{\tau_s}}$$
(3.1)

where  $N_{f,s}$  denotes the probability that a scintillation photon is emitted by the fast and slow component, respectively(such that  $N_f + N_s = 1$ ), and  $\tau_{f,s}$  are the corresponding decay time constants. Typical values for  $\tau_{f,s}$  are 2 – 5 ns and 10 – 40 ns, respectively, and 0.6 – 0.8 for  $N_f$  [15]. While the decay time constants are the same for all particles, it is possible to specify an individual ratio between the two exponential functions for alpha particles and protons. Thus, different particles can be simulated with different PDFs, which is necessary for the pulse shape dicrimination of two particles (see Chapter 4).

The quenching effect is implemented through the Birks formula [51]:

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + k_b \frac{dE}{dx}} \tag{3.2}$$

where  $\frac{dL}{dx}$  is the number of photons emitted per unit path length, A is the light yield and  $k_b$  is a specific parameter for the scintillator.

If the wavelength of a photon is larger than the typical atomic spacing, it is treated as a so-called optical photon in GEANT4. For these optical photons absorption and Rayleigh scattering are included. In this simulation the Rayleigh scattering and the absorption length were set to 20 m and the refractive index to n = 1.565 [15].

### **3.4** Neutron Production

In order to simulate the fast neutron background in LENA, the muoninduced neutron production needs to be simulated. Instead of simulating the muon spectrum at a certain depth, the neutron production rate can be approximated by using the muon mean energy at a given depth [45]. Therefore, the neutron production by muons with a constant energy between 150 GeV and 338 GeV, corresponding to the mean muon energy at a depth of 1 km w.e. to 6 km w.e., was simulated. As many neutrons are produced in electromagnetic and hadronic cascades, which need some space to develop, the muon has to pass a certain thickness of rock before an equilibrium between neutron and muon flux is established. Otherwise, the muon track should not be too long, so that the relative muon energy loss is small and the muon energy can be considered as constant along the track. Therefore, the muons were propagated through 15 m of limestone rock (CaCO<sub>3</sub>, density 2.73  $\frac{g}{cm^3}$ ).

The energy, momentum direction, origin position, and the production process of the generated neutrons were saved to a ROOT tree, for further analysis with the ROOT data analysis framework [52]. The number of neutrons that were produced in a given event were also saved to a second ROOT tree.

GEANT4 terminates the track of a neutron after an inelastic scattering process. The scattered neutron is treated as a secondary particle and gets a new track. Therefore, the first of the secondary particles generated in an inelastic neutron scattering process was considered as the incident neutron and was not counted as a produced neutron, in order to avoid double counting of neutrons.

The neutron production of  $1.5 \cdot 10^5$  muons was simulated at five different muon energies (150 GeV, 226 GeV, 273 GeV, 300 GeV, 338 GeV). These muon energies correspond to the mean muon energies at 1, 2, 3, 4 and 6 km w.e. depth.

Figure 3.4 shows the average neutron production rate along a muon track with  $E_{\mu} = 300 \text{ GeV}$ .

After a steep rise of the production rate over the first 2 m of the muon track,



Figure 3.4: Average neutron production along a muon path with  $E_{\mu} = 300 \text{ GeV}$ . The blue region represents the analysis area, which determines the neutron production yield per muon and unit path length shown in Figure 3.5. The first two meters of the muon track are not included in the analysis area, as the electromagnetic and hadronic showers need some space to develop, causing a steep rise of the production rate until an equillibrium between neutron and muon flux is established.

the neutron yield is relatively constant. The reason for this characteristics is that the muon induced hadronic and electromagnetic showers need some space to develop, and therefore much less neutrons are produced at the beginning of the muon track. Therefore only neutrons produced after the first 2 m of a muon track (the blue region in Figure 3.4) were used to determine the neutron production yield.

The results for this yield, plotted as neutrons produced per muon and unit path length  $(1\frac{g}{cm^2})$ , is shown in Figure 3.5.



Figure 3.5: Average number of neutrons produced by a muon per unit path length  $(1\frac{g}{cm^2})$  in limestone rock, as a function of the muon energy. The black graph shows the total neutron yield and the red graph depicts the neutron yield for neutrons with E > 40 MeV.

If LENA is build at 4 km w.e. depth, a muon that passes the rock next to the detector will produce on average 11.9 neutrons for 100 m track length, out of them 2.9 with higher energies of E > 40 MeV. The neutron yield for high energies is important (E > 40 MeV), as preceeding Monte Carlo simulations have shown that the probability to reach the target volume is insignificant for neutrons with E < 40 MeV.

The energy dependence of the simulated neutron production rate can be approximated by a power law:

$$N_n \propto E^{\alpha} \tag{3.3}$$

with  $\alpha = 0.88 \pm 0.01$ .

Equation (3.3) also applies for the production rate of the higher energetic neutrons (E > 40 MeV), with  $\alpha = 0.91 \pm 0.01$ .

The results for the neutron production rate are in good agreement with other simulations that used the FLUKA code [45]. In [45], the resulting energy dependence of the neutron yield was  $\propto E^{0.79}$  and the neutron production rate was  $4.0 \cdot 10^{-4}$  neutrons/muon/(g/cm<sup>2</sup>) for 280 GeV muons in marl rock, which consists mainly of CaCO<sub>3</sub>, approximately 5% less than the resulting neutron yield of the present simulation (see Figure 3.5).

### **Energy Spectrum**

Figure 3.6 shows the simulated neutron spectrum that was generated by 300 GeV muons.



Figure 3.6: Energy spectrum of neutrons that were produced by muons with  $E_{\mu} = 300 \text{ GeV}$  for neutron energies below 1 GeV.

It decreases with the energy and extends to kinetic energies in the GeV region. The production rate there is of special interest as the mean free path of neutrons increases with the energy [45] and thus the probability that they propagate into the target volume.

### **Neutron Multiplicity**

Figure 3.7 shows the neutron multiplicity, which is defined as the number of neutrons that are produced by a single muon track.

While every muon produces on average  $\sim 12$  neutrons over 100 m track length, there are also muons that produce several hundreds of neutrons. There is a certain probability that a muon transfers a large fraction of its



Figure 3.7: The neutron multiplicity that is defined as the number of neutrons that are produced by a single muon track, at  $E_{\mu} = 300 \text{ GeV}$ 

energy into a hadronic or electromagnetic cascade. Because the number of produced neutrons depends on the energy content of the cascade, the neutron multiplicity will be large in these case.

### **Neutron Production Processes**

As mentioned above, there are several neutron production processes. Only a small fraction of the neutrons is produced directly by a muon, the majority is produced through secondary reactions in hadronic and electromag-

Production Process	Relative Contribution in $\%$
Gamma Nuclear	28.4
Neutron Inelastic	25.9
Pion Inelastic	23.4
Pion Absorption	8.4
Proton Inelastic	5.7
Muon Nuclear	7.3
Others	0.9

Table 3.1: Relative contribution of individual processes to the total neutron production yield at  $E_{\mu} = 300 \,\text{GeV}$ .

netic cascades, induced by muons. Table 3.1 shows the most important production processes and their relative contribution to the neutron yield, at  $E_{\mu} = 300 \text{ GeV}$ . About 28% of the neutrons are produced by the interaction of high energetic gammas with a nucleus (Gamma Nuclear). Another important secondary reaction is the inelastic scattering of neutrons and pions (Neutron and Pion Inelastic) on a nucleus. Together they contribute to ~ 49% of the neutron yield. The absorption process of a  $\pi^-$  on a nucleus (Pion Absorption), the inelastic scattering of protons on a nucleus (Proton Inelastic) and the direct production of a neutron by the muon (Muon Nuclear, see Section 3.1) contribute to the neutron production rate with about 6% to 8%.

#### Angular Distribution

In Figure 3.8 the simulated result for the angular distribution of the generated neutrons is shown.  $\theta(\mu, n)$  is the angle between the momentum direction of the incident muon and the generated neutron.



Figure 3.8: Angular distribution of muon-induced neutrons at  $E_{\mu} = 300 \text{ GeV}$ .

While most neutrons are directed forwards, there is also the possibility that the generated neutron is directed backwards relative to the muon direction of flight, as neutrons are not directly knocked out of the nucleus. Instead, the incident particle transfers energy to the nucleus, which gets consequently excitated. The neutron is then emitted by deexcitation of the nucleus. The angular distribution of the emitted neutrons depends both on the generation process and the muon energy. As the deexcitation is calculated in the rest frame, the neutron momentum has to be lorentz-transformed to the laboratory frame.

### 3.5 Neutron Propagation into the Detector



Figure 3.9: Schematic cross section through the LENA detector, the same colour codes as in Figure 3.3 apply. For the simulation only neutrons generated in the grey region were considered.

The starting point of the neutron was chosen randomly in a 1.96 m thick cylinder around the muon veto (see Figure 3.9). Previous simulations have shown that neutrons which were produced farther away from the detector do not need to be considered, as the majority will be absorbed in the rock before they reach the detector. The neutron energy and momentum direction was chosen randomly according to the previously simulated neutron spectrum. Only neutrons with E > 40 MeV were simulated, as the range of lower energetic neutrons is too small to reach the target volume. Neutron tracks that pointed away ( $2\pi$  solid angle) from the detector were also not followed, as previous simulations have shown that the chance that these neutrons are backscattered and reach the detector is with  $\sim 2\%$  negligible. Secondary neutrons were also followed in the simulation. In the case of multiple neutrons, the stopping point of the neutron reaching the smallest radius was chosen.

20 million neutrons above 40 MeV were simulated using the energy spectrum and angular distribution corresponding to a muon mean energy of 300 GeV (4 km w.e.). Assuming that all tracks are perfectly vertical, the muon rate on this  $226 \text{ m}^2$  area is  $1.45 \cdot 10^{-2} \text{ s}^{-1}$  at 4 km w.e. depth. Using the results



Figure 3.10: Simulated range of muon-induced fast neutrons in LENA, with PXE used as scintillator and buffer liquid. Additionally, an exponential fit is plotted. The red region represents the neutrons that reached the target volume. Statistics corresponds to  $\sim 15$  years at 4 km.w.e. depth.

from the previous simulation (see Section 3.4),  $\sim 1.3 \cdot 10^6$  neutrons per year with E > 40 MeV are produced in the mantle. Thus, the statistics of the simulation corresponds to  $\sim 15$  years.

Figure 3.10 shows the simulated range of muon-induced neutrons in LENA using PXE as scintillator and buffer liquid. The minimal radius of a neutron track's end point is  $\sim 6 \,\mathrm{m}$ , which is far inside the target volume, and many neutrons reach the target volume. The neutron range can be fitted with an exponential function  $a \cdot e^{\frac{r}{\lambda}}$ , where a is a constant factor,  $\lambda$  is the mean free path and r is the radius of the neutron track's end point. In PXE the mean free path length  $\lambda$  is  $0.676 \pm 0.005$  m and in LAB it is  $0.687 \pm 0.006$  m. For comparison, in the LVD experiment a mean free path length of  $0.634 \pm 0.012$  m was measured, with a different scintillator  $(C_{10}H_{20})$  [53]. Between  $r \sim 13 \,\mathrm{m}$ and  $r \sim 15 \,\mathrm{m}$  the fit describes the simulated neutron range very good, but below  $r \sim 13$  m the fit function decreases faster with the radius than the simulated neutron range. If the fit range is constricted from 9 m to 13 m the mean free path length increases in PXE to  $0.778 \pm 0.016$  m. The reason for this characteristic is that the neutrons are not monoenergetic and that the mean free path length increases with the energy. Therefore, the average neutron energy increases with the distance to the muon track as well as the average mean free path length.

The initial energy spectrum of the neutrons that reached the target volume



Figure 3.11: Initial energy spectrum of the neutrons that reached the target volume.

is shown in Figure 3.11. Only a small percentage of the neutrons had a energy below 100 MeV and almost no neutron below 50 MeV reached the target volume, which shows that neutrons below E < 40 MeV can be safely neglected. The maximum is located at ~ 200 MeV and is caused by the increasing range of the neutrons with energy and the downward slope of the initial neutron energy spectrum (see Figure 3.6).

Figure 3.12 shows the energy deposited by the neutrons in the scintillator volume. It is important to note that this is the complete energy deposition and does also include energy that is not transferred into photons and is therefore not visible in the detector. Neutrons loose energy mainly by elastic scattering off protons and by inelastic scattering off carbon in the scintillator. In the first case the visible energy is quenched by a factor of  $\sim 2$ . In the latter case, the quenching factor depends on the energy transferred to the carbon nucleus and the subsequent type of deexcitation. If  $\alpha$ -particles are emitted the quenching factor is in the order of 10, if gammas are emitted it is in the order of 1. On average, the resulting total quenching factor is about 2-4.

The maximum of the deposited energy is located at  $\sim 70$  MeV. This maximum is caused by the maximum of the initial energy spectrum (see Figure 3.11) and the average energy loss of a neutron on the way from the rock to the target volume.



Figure 3.12: Total energy deposited by neutrons in the scintillator volume of LENA. The effective visible energy will be quenched by a factor of  $\sim 2-4$ .

### 3.6 Background Rates in LENA

Table 3.2 shows the resulting neutron background rates in LENA at 4 km w.e. depth, as a function of the fiducial volume with PXE used as scintillator solvent. The neutron background rates in LENA with LAB used as scintillator solvent are shown in Table 3.3. Around 170 neutrons per year reach the target volume in PXE, in LAB this rate increases to ~ 200 per year. Because the density of PXE ( $\rho_{PXE} = 985 \frac{g}{1}$ ) is greater than the density of LAB ( $\rho_{LAB} = 860 \frac{g}{1}$ ) the self-shielding effect of PXE is larger. The neutron background rate is therefore higher in LAB.

The difference in neutron background rate between the two solvents increases with the shielding. While the neutron background rate is only  $\sim 20\%$  larger for LAB if the fiducial volume radius is set to 13 m, it is  $\sim 90\%$  larger if the fiducial volume has a radius of 10 m.

Table 3.2 and 3.3 also include the event numbers in two energy bins corresponding to the geoneutrino and DSNB detection windows, respectively. Considering the possible range in quenching factors (see Section 3.5), a deposited energy of 2 MeV - 9.6 MeV corresponds to a visible energy between 1.8 MeV and 3.2 MeV in which the geoneutrino signal is expected. The 10 MeV - 25 MeV DSNB detection window corresponds to a deposited neutron energy between 20 MeV and 100 MeV.

As about 1000 geo- $\bar{\nu}$  events per year are expected in LENA, fast neutrons provide a negligible background for the geoneutrino detection.

Fiducial Volume	Number of neutrons [/y]		
Radius [m]	Total energy range	Geo- $\bar{\nu}$ -region	DSNB-region
13	166	5.2	70
12	54	0	14
11	15	0	1.7
10	3.9	0	0.3
9	0.9	0	0.1

Table 3.2: Neutron background rates per year in LENA as a function of the fiducial volume radius with PXE as scintillator solvent. The Geo- $\bar{\nu}$ -region corresponds to  $2 \text{ MeV} < E_n < 9.6 \text{ MeV}$ , the DSNB region to  $20 \text{ MeV} < E_n < 100 \text{ MeV}$ , due to the neutron quenching.

Fiducial Volume	Number of neutrons [/y]		
Radius [m]	Total energy range	Geo- $\bar{\nu}$ -region	DSNB-region
13	200	6.2	83
12	69	0	18
11	21	0	2.7
10	7.4	0	0.5
9	2.8	0	0.1

Table 3.3: Neutron background rates per year in LENA as a function of the fiducial volume radius with LAB as scintillator solvent. The Geo- $\bar{\nu}$ -region corresponds to  $2 \text{ MeV} < E_n < 9.6 \text{ MeV}$ , the DSNB region to  $20 \text{ MeV} < E_n < 100 \text{ MeV}$ , due to the neutron quenching.

The situation is quite different for the detection of the DSNB, as the background rate in the DSNB-region is much greater, and the expected signal is much smaller (6-13 events per year). If the neutron background can not be reduced, the radius of the fiducial volume needs to be set to 10 m, to achieve a signal-to-background (S/B) ratio of better than 10:1. This would mean that more than 40% of the target volume would be lost. In this case, the remaining neutron background in LAB would be  $\sim 60\%$  higher than in PXE. Thus, from the aspect of neutron background, PXE is the preferred scintillator.

Another possibility is to increase the water shielding around the buffer. In the pre-design study for the Pyhäsalmi location [22], the water Čerenkov muon veto has a elliptically shape with at least 2 m shielding. Due to this geometry, the effective shielding would be larger than the 2 m that were assumed in this simulation. The presented results are therefore a conservative estimation. Nevertheless, they show that the muon-induced neutron background is a central issue for the detection of rare events like the DSNB, in LENA.

### **3.7** Identification of Neutron Events

As neutron interactions in the scintillator differ from those of a positron emitted in the inverse beta decay reaction, it might be possible to distinguish neutron from  $\bar{\nu}_e$  events by the use of special discrimination criteria. Depending on the efficiency of the methods used, the fast neutron background could be reduced considerably.

### 3.7.1 Multiple Neutron Capture Events

If a muon-induced neutron enters the scintillator volume, it can generate secondary neutrons by inelastic scattering off carbon. Like the primary neutron, these secondary neutrons are captured on free protons and are thus easily detected (see Figure 3.13). Due to the kinematics of the reaction, a neutron from an inverse-beta decay reaction has not enough energy to generate secondary neutrons. Therefore, events with more than one neutron capture signal within 1 ms (corresponding to  $\sim 5$  times the capture time of a neutron in common liquid scintillators) can be rejected as fast neutrons. In principle it is possible that a DSNB-event is misidentified as a fast neutron event, through random coincidence due to intrinsic radioactivity. But as the time window around the potential DSNB-event is with 1 ms very short and the radioactive purity level of LENA will be very high, the probability for random coindicences is negligible.



Figure 3.13: Simulated photon signal of a neutron event, where a secondary neutron was generated. The signal of the two capture processes is clearly seperated which allows to distinguish this event from a  $\bar{\nu}_e$  event.

The neutron background rates after application of the neutron capture cut are shown in Table 3.4 for PXE and Table 3.5 for LAB as scintillator solvent. The efficiency of this method depends on the neutron energy, as higherenergetic neutrons are more likely to produce secondary neutrons. Since the average energy of a neutron increases with the shielding, the efficiency of this method depends on the fiducial volume radius. For the smallest fiducial volume, a neutron background rejection efficiency of  $\sim 60\%$  can be achieved with this method.

### 3.7.2 Pulse Shape Analysis

The light decay curve caused by a particle interacting in a liquid scintillator depends on its energy deposition per unit path length  $\left(\frac{dE}{dx}\right)$  and thus on the particle mass and charge. This allows the discrimination of different particles by pulse shape analysis (see Figure 3.14).

The probability density function (PDF) F(t) of the photon emission process in liquid scintillator can be described by the sum of several exponential decays [15]:

$$F(t) = \sum_{i} \frac{N_i}{\tau_i} \cdot e^{-\frac{t}{\tau_i}}$$
(3.4)

where  $\tau_i$  is the decay time constant of the exponential function i and N<sub>i</sub> its

	Number of neutrons [/y]	
Fiducial Volume	Total	$20\mathrm{MeV} < \mathrm{E}_n < 100\mathrm{MeV}$
Radius [m]	energy range	DSNB-region
13	95	50
12	21	8.9
11	4.5	1.1
10	1.2	0.2
9	0.3	0.1

Table 3.4: Neutron background rates per year in LENA as a function of the fiducial volume radius, with PXE as scintillator solvent and applying a multiple neutron capture veto. The indicated neutron energy region corresponds in visible energy to the DSNB detection window.

	Number of neutrons [/y]	
Fiducial Volume	Total	$20\mathrm{MeV} < \mathrm{E}_n < 100\mathrm{MeV}$
Radius [m]	energy range	DSNB-region
13	119	62
12	28	12
11	6.9	1.9
10	2.2	0.4
9	0.7	0.1

Table 3.5: Neutron background rates per year in LENA as a function of the fiducial volume radius, with LAB as scintillator solvent and applying a multiple neutron capture veto. The indicated neutron energy region corresponds in visible energy to the DSNB detection window.

relative contribution to the PDF (such that  $\sum_i N_i = 1$ ). The exponential function with the shortest decay time constant is usually referred to as the fast component, the other exponential functions are the so-called slow component. Heavier particles have a larger ratio between the slow and the fast component of the PDF than lighter particles. Typically 60% to 80% of the photons are emitted by the fast component, the exact value depends on the particle type and the scintillator. The fast time constant is usually in the order of 2 ns to 5 ns, the slow time constants are in the range of 10 ns to 200 ns.

Neutrons generate scintillation light only indirectly by elastic scattering off protons and inelastic scattering off carbon, where amongst others gammas, protons and  $\alpha$ -particles are produced. As the neutron looses its energy in several elastic and inelastic scattering processes, it is possible to get double peak structures if the time difference between two scattering processes is of the order of several ns or more. Consequently, neutrons feature a different pulse shape than positrons generated in inverse beta decay reactions. This should allow pulse shape discrimination of neutron and  $\bar{\nu}_e$  events. A detailed analysis for LENA will be presented in Chapter 5.



Figure 3.14: Comparison of the typical pulse shapes for  $\alpha$ -particles, protons and electrons in liquid scintillator [15]

### Chapter 4

# Neutron-Gamma Pulse Shape Discrimination in Liquid Scintillators

It was shown in Chapter 3 that muon-induced neutrons provide a background for the detection of rare  $\bar{\nu}_e$  events in LENA. A possible way to reduce this background is to discriminate neutron from  $\bar{\nu}_e$  events by pulse shape analysis (see Section 3.7.2). Therefore, an experiment was performed in which the efficiency of a neutron-gamma pulse shape discrimination in a small liquid-scintillator detector was examined. The results were compared to a simulation of the same setup in order to determine the necessary scintillation parameters. In the following, these values could be transferred to the GEANT4 simulation of LENA to investigate pulse shape discrimination (see Chapter 5).

### 4.1 Tail-to-total Discrimination Method

In a liquid-scintillator detector, the typical pulse shape depends on the particle type (see Section 3.7.2). The ratio between the slow and the fast component of the probability density function (PDF) is larger for heavier particles. In the tail-to-total discimination method the photon signal is integrated over two different time intervals. One interval encompasses the complete pulse, while the other interval encompasses only the last part of it, the so-called tail (see Figure 4.3). Then the ratio between the "total" and the "tail" interval is calculated [16]. Based on the PDF (see equation (3.4)) of the photon emission process, the tail-to-total ratio R is defined as:

$$R = \sum_{i} N_i e^{-\frac{t}{\tau_i}} \tag{4.1}$$

where t is the start time of the "tail" interval.

As the amplitudes  $N_i$  depend on the particle type, the tail-to-total ratio is characteristical for the particle type. Heavier particles have a higher tail-tototal ratio than lighter particles, as the contribution of the slow component to the PDF is larger (see Figure 3.14). Thus, a discrimination between two particle types is possible by the comparison of the tail-to-total ratios.

### 4.2 Experimental Setup

The experiment was setup at the MLL (Maier-Leibniz-Laboratorium) in the tandem accelerator building in Garching. The setup consists of a hexagonally shaped container filled with liquid scintillator that is coupled directly to a Philips XP 3461 B PMT via a perspex window. The container is 50 mm high and its radius is 45.5 mm. As it is coupled directly to the PMT on one side, the optical coverage is approximately 23% (see Figure 4.1).



Figure 4.1: Schematic experimental setup. The Am-Be source emits neutrons and gammas, which generate light in the liquid scintillator sample. The scintillation light is detected by the PMT, which is coupled directly to the liquid scintillator.

An Am-Be source is used, as it emits both neutrons and gamma rays. <sup>241</sup>Am is an  $\alpha$ -emitter with 432.2 years half-life. The  $\alpha$ -particle is subsequently captured on a <sup>9</sup>Be nucleus, resulting in the emission of a neutron and a gamma quantum:

$$\alpha + {}^{9} \operatorname{Be} \to {}^{13} \operatorname{C}^{*} \to {}^{12} \operatorname{C} + n + \gamma \tag{4.2}$$

The emitted neutrons have a continious spectrum up to 10 MeV with 5 MeV mean energy (see Figure 4.2). The energy of the emitted gamma quantum is 4.44 MeV, corresponding to the first excited state of <sup>12</sup>C [54].



Figure 4.2: Energy spectrum of the neutrons emitted by the Am-Be source. The mean neutron energy is 5 MeV [55].

Two liquid scintillators were used in this experiment. PXE<sup>1</sup>(phenyl-xylylethane) and LAB<sup>2</sup> (linear alkylbenzene), both with  $10 \frac{g}{1}$  PPO (2,5-diphenyloxazole). The typical pulse shape depends on the PPO concentration, but between  $2 \frac{g}{l}$  and  $10 \frac{g}{l}$  the differences are rather small for both PXE and LAB [15].

Due to the small volume of the liquid scintillator sample, the majority of neutrons and gammas scatter off only once in it.

<sup>&</sup>lt;sup>1</sup>Produced by Dixie Chemical Co., Houston TX (US)

<sup>&</sup>lt;sup>2</sup>Produced by Petresa Canada, part of CEPSA Group, Becancour QC(CDN)

### 4.3 Data Acquisition and Analysis

The signal from the PMT (anode) is digitalized by a VME-based ADC module (SIS3320, Struck, Germany) with 200 MHz sampling rate, 12-bit resolution and an integrated trigger. A VME controller links the system to a PC, where the data is acquired with a software that was written by C. Ciemniak [56]. The first 250 ns of each pulse recorded are used to calculate the baseline, which is subtracted afterwards. In the next step, the integral of the whole pulse from 350 ns to 630 ns is calculated. Afterwards, the "tail" interval from 400 ns to 630 ns is integrated and subsequently the tail-to-total ratio is calculated (see Figure 4.3).



Figure 4.3: An example pulse with subtracted baseline. The start of the pulse is marked in green, the end of the pulse in red. The blue region represents the "tail" interval for the calculation of the tail-to-total ratio.

The experiment was calibrated using a <sup>22</sup>Na source, emitting 1275 keV gamma rays that undergo Compton scattering in the liquid scintillator. The energy of the Compton scattered electron and thus the energy deposition E in the scintillator is:

$$E(\cos\theta) = E_{\gamma} - \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e}(1 - \cos\theta)}$$
(4.3)

where  $E_{\gamma}$  is the incident gamma energy,  $m_e = 551 \text{ keV}$  the electron mass and  $\theta$  the scattering angle.

Thus, the maximum energy deposit  $E_{max}$ , normally referred to as the Compton edge, is at  $\theta = 180^{\circ}$ :

$$E_{max} = E_{\gamma} - \frac{E_{\gamma}}{1 + \frac{2E_{\gamma}}{m_e}} = \frac{E_{\gamma}}{\frac{m_e}{2E_{\gamma}} + 1}$$
(4.4)

For  $E_{\gamma} = 1275 \text{ keV}$ , the maximum recoil energy is  $E_{\text{max}} = 1062 \text{ keV}$ .

In the spectrum recorded of the <sup>22</sup>Na source, the known energy at the Compton edge can be used to determine the relation between the integral of the signal and the energy deposited (see Figure 4.4).

As the deposited energy is proportional to the integrated signal s, it can be determined from the latter by the following equation:



 $E = s \cdot \frac{1062 \,\mathrm{keV}}{s_{compton \, edge}}$ (4.5)

Figure 4.4: Calibration of the experimental setup with PXE used as liquid scintillator. The energy resolution  $\frac{\Delta E}{E}$  is proportional to  $\frac{1}{\sqrt{N}}$ , where N is the number of registered photons in the PMT, and the gamma quant scatters only once in the detector. Thus, the Compton egde of <sup>22</sup>Na gamma rays, at 1062 keV, is fitted with a Gauss function, in order to determine the relation between the integral of the signal and the deposited energy

#### **4.4** Results

Figure 4.5 shows the tail-to-total ratio of the measured pulses with PXE used as liquid scintillator and an energy threshold of 1 MeV. The gamma and neutron events separate into two peaks that have a small overlap. As the Compton scattered electrons feature a lower charge-to-rest-mass ratio than the recoil protons from neutron scattering, the left peak in Figure 4.5 belongs to gamma events and the right one to neutron induced events. Each peak can be fitted with a Gaussian:

$$N \cdot \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4.6}$$



Figure 4.5: Tail-to-total ratios of the measured pulses in PXE. The energy threshold was set to 1 MeV. The two peaks from gamma (left peak) and neutron (right peak) events are clearly seperated, such that 99.5% of the neutron events can be rejected, if 97.8% of the gamma events are accepted. Each peak was fitted with a Gaussian function (the corresponding sum of both functions is shown here).

where N is the number of events,  $\mu$  is the expected value and  $\sigma$  is the standard deviation. The resulting fit values for the gamma peak are  $\mu_{\gamma} = (8.6 \pm 0.017) \cdot 10^{-2}$ ,  $\sigma_{\gamma} = (1.0 \pm 0.012) \cdot 10^{-2}$ , and  $\mu_n = 0.16 \pm 2.4 \cdot 10^{-4}$ ,  $\sigma_n = (1.7 \pm 0.019) \cdot 10^{-2}$  for the neutron peak, respectively.

The separation efficiency between the two peaks can be described by the peak distance parameter parameter D:

$$D = \frac{\mu_n - \mu_\gamma}{\sqrt{\sigma_n^2 + \sigma_\gamma^2}} \tag{4.7}$$

which denotes the distance between the two peaks, in terms of the mean standard deviation  $\sqrt{\sigma_n^2 + \sigma_\gamma^2}$ .

Thus, the distance between the gamma and the neutron peak in Figure 4.5 is D=3.87. If one accepts only events with a tail-to-total ratio that is smaller than  $\mu_{\gamma} + 2\sigma_{\gamma}$ , 97.8% of all gamma events are accepted, while 99.5% of all neutron events are rejected. Almost all neutron are identified, losing only 2.2% of gamma events to false identification.

The peak distance D between the gamma and the neutron peak and the corresponding efficiencies of the neutron-gamma discrimination were calculated for five different energy intervals between 0.5 MeV and 3.5 MeV visible energy. The resulting energy dependence of the distance D is shown in Figure



Figure 4.6: Energy dependence of the peak distance parameter D between gamma and neutron peak (see equation(4.7)) in PXE (plotted in black) and LAB (plotted in red). The distance  $\mu_n - \mu_\gamma$  between the peaks as well as  $\sqrt{\sigma_n^2 + \sigma_\gamma^2}$  decreases with the visible energy, which leads to the peak at ~ 2 MeV visible energy in PXE. In contrast to that, D increases with the visible energy in LAB, because  $\sqrt{\sigma_n^2 + \sigma_\gamma^2}$  decreases faster than  $\mu_n - \mu_\gamma$ .

Visible	Neutron rejection efficiency	
Energy $[MeV]$	in PXE $[\%]$	in LAB $[\%]$
0.5-1.1	99.80	93.28
1.1 - 1.7	99.97	98.27
1.7 - 2.3	99.99	99.05
2.3 - 2.9	99.99	99.33
2.9 - 3.5	99.98	99.36

Table 4.1: Energy dependence of the neutron rejection efficiency in PXE and LAB with 97.8% gamma acceptance.

4.6 for PXE and LAB. The corresponding efficiencies of the neutron-gamma discrimination is shown in Table 4.1.

As the tail-to-total ratio depends on the energy deposition per unit path length  $\frac{dE}{dx}$ ,  $\mu_{n,\gamma}$  depends on  $\frac{dE}{dx}$  of the recoil proton and the recoil electron, respectively. For electrons, the energy dependence of  $\frac{dE}{dx}$  is insignificant between 0.5 MeV and 3.5 MeV [57]. But the energy loss  $\frac{dE}{dx}$  of the protons decreases with the proton energy in the relevant energy region [57]. Thus, the distance  $\mu_n - \mu_{\gamma}$  between the neutron and the gamma peak decreases with energy.

But  $\sigma_{n,\gamma}^2$  decreases also with the energy deposited, because the enlarged number of photons minimizes the statistical fluctuations around the ideal PDF.

In LAB, this effect is strong enough to compensate the decreasing distance between the gamma and the neutron peak with rising energy. Therefore, the efficiency of the neutron-gamma discrimination increases with the visible energy in LAB.

In PXE the peak distance D gets maximal at  $E_{\text{visible}} \sim 2 \text{ MeV}$  and then starts to decrease, because the distance between the peaks  $\mu_n - \mu_\gamma$  decreases faster than  $\sqrt{\sigma_n^2 + \sigma_\gamma^2}$ .

The efficiency of the neutron-gamma discrimination is higher in PXE than in LAB (see Table 4.1). Nevertheless, in both scintillators more than 99% of the neutron events with a visible energy between 2 MeV and 3.5 MeV can be rejected with a 97.8% acceptance of the gamma events.

### 4.5 Monte Carlo Simulation

Besides the measurements, the experiment was reproduced with the same program used for the simulation of the fast neutron background (see Section 3). The simulated detector geometry consists of a 50 mm high cylinder with 91 mm in diameter, which is filled with PXE or LAB. Every photon that hits the walls of the cylinder is counted and the time of the hit is saved. In the simulation an effective light yield was used, which is determined by the physical light yield (~ 10000 photons per MeV), the optical coverage ~ 23% and the quantum efficiency of the PMT ~ 20% [15]. The best reproduction of the measured data could be achieved with an effective light yield of 440 photons per MeV for PXE and 370 photons per MeV for LAB.

Scattering and absorption processes were also included in the simulation. The Rayleigh scattering length and absorption length were set 20 m for both scintillators. Therefore, the effects of both processes should be negligible.

The proton quenching was described by the Birks formula (see equation (3.2)), setting  $k_b = 0.15 \frac{\text{mm}}{\text{MeV}}$  for both PXE and LAB [58].

A time jitter of 3 ns was added to the hit time of the photon, in order to simulate the time resolution of the PMT that was used in the experiment.

A PDF F(t) featuring two decay terms was assumed for the scintillation emission:

$$F(t) = \frac{N_f}{\tau_f} e^{-\frac{t}{\tau_f}} + \frac{N_s}{\tau_s} e^{-\frac{t}{\tau_s}}$$

$$\tag{4.8}$$

 $N_{f,s}$  denotes the probability that a scintillation photon is emitted by the fast and slow component, respectively, and  $\tau_{f,s}$  are the corresponding decay time constants. For PXE,  $\tau_f$  was set to 2.9 ns and  $\tau_s$  was set to 29 ns and for LAB,  $\tau_f$  was set to 3.7 ns and  $\tau_s$  was set to 31 ns, as these values were derived from a fit of the average pulses recorded in the experiment (for comparison,  $\tau_f$ was determined to ~ 2 ns for both PXE and LAB in [15] using a PDF with 4 exponential functions).

The value of  $N_f$  depends on the particle type and for protons also on the energy. For electrons, it was set to 0.8 for PXE and to 0.72 for LAB (these values were also derived from a fit of the average pulses recorded in the experiment).

The energy dependence of the measured tail-to-total ratio for protons can be fitted with the sum of an exponential function and a constant function (see Figure 4.7). As the tail-to-total ratio is defined by:

$$\sum_{i} N_{i} e^{-\frac{t}{\tau_{i}}} \stackrel{t \gg \tau_{f}}{\approx} N_{s} e^{-\frac{t}{\tau_{s}}}$$

$$(4.9)$$

it is proportional to  $N_s$ . Thus, as  $\tau_s$  is energy independent, the energy dependence of  $N_s$  and  $N_f$  can also be described by the sum of an exponential and a constant function:

$$N_f = p_0 + p_1 \cdot e^{p_2 \cdot \mathcal{E}_{\text{vis}}} \tag{4.10}$$

where  $p_0$ ,  $p_1$  and  $p_2$  are scintillator dependent parameters, and  $E_{vis}$  is the visible energy.

For PXE  $\rm N_{f}$  was calculated by

$$N_f = 0.744 - 0.12 \cdot e^{\frac{-0.00054}{\text{keV}} \cdot E_{\text{vis}}}$$
(4.11)

and for LAB by

$$N_f = 0.6895 - 0.086 \cdot e^{\frac{-0.0003}{\text{keV}} \cdot E_{\text{vis}}}$$
(4.12)

because with these values for  $p_0$ ,  $p_1$  and  $p_2$  an optimal reproduction of the experimentally measured tail-to-total ratio was achieved.

The simulation was calibrated in the same way as the experimental setup (see Section 4.3).



Figure 4.7: Measured energy dependence of the tail-to-total ratio for neutrons in PXE. A fit based on the sum of an exponential and a constant function  $(p_0 + p_1 \cdot e^{p_2 \cdot \mathbf{E}_{vis}})$  is shown.

 $2 \cdot 10^5$  gamma particles with  $E_{\gamma} = 4.44$  MeV and  $2 \cdot 10^5$  neutrons with  $E_n = 10$  MeV were simulated for each scintillator. For the calculation of the tail-to-total ratio the start of the "tail" interval was set to 15 ns.

The reproduced values for  $\sigma_{n,\gamma}$  were smaller than the measured ones, because effects of the PMT and electronics that influence the experimental result are not reproduced in the simulation. Pre- and afterpulses of the PMT are omitted, and the start time of the pulse is always determined perfectly. Thus a systematic error was added to the tail-to-total ratio to compensate the lack of these error sources. An optimal reproduction was achieved when the systematic error was set to  $\sigma = 4 \cdot 10^{-3}$ .

As for the experimental data, the distribution of the tail-to-total ratio was fitted with the sum of two Gauss functions, for reproducing the neutron and gamma peaks.

The resulting simulated energy dependence of the distance D between the gamma and the neutron peak is shown in Figure 4.8 for PXE and in Figure 4.9 for LAB.

The simulated peak distance D differs from the experimentally measured one by 2% to 10%, depending on the visible energy. The decrease of the peak distance D in PXE above ~ 2 MeV is reproduced by the simulation, with a small difference in the exact energy dependence of D. As no background sources are simulated,  $\sigma_{\gamma,n}$  shows a slightly different energy dependence in the simulation. These are probably caused by the neglection of electronics effects in the simulation. As a good agreement between the experimental and the



Figure 4.8: Simulated energy dependence of the peak distance parameter D between gamma and neutron peak (see equation(4.7)) with PXE used as scintillator. The dashed line shows the experimental results. The peak at  $\sim 2 \,\text{MeV}$  visible energy is reproduced by the simulation. Overall the simulated peak distance differs from the experimentally measured one by 2%-10%, depending on the visible energy.



Figure 4.9: Simulated energy dependence of the peak distance parameter D between gamma and neutron peak (see equation(4.7)) with LAB used as scintillator. The dashed line shows the experimental results. The simulated peak distance differs from the experimentally measured one by 3%-7%, depending on the visible energy

simulated results is achieved, a simulation of the pulse shape discrimination between fast neutron and  $\bar{\nu}_e$  events in LENA should obtain realistic results. The results of this simulation will be presented in Chapter 5.

## Chapter 5

# Pulse Shape Discrimination of Neutron and $\bar{\nu}_e$ Events in LENA

The capability to distinguish neutron events from gamma events in a small liquid-scintillator detector by pulse shape analysis was demonstrated in Chapter 4. At visible energies between 2 MeV and 3.5 MeV, neutron rejection at an efficiency level of more than 99% was reached, while a gamma acceptance of 97.8% remained.

In this Chapter the results of a Monte Carlo simulation will be presented that has analyzed the efficiency of a pulse shape discrimination between fast neutrons and  $\bar{\nu}_e$  events in LENA. As LENA is a 50 kt detector, absorption and scattering of the scintillation light becomes important. Light propagation effects could be neglected in the experiment described in Chapter 4, because of the small detector volume. Moreover, the neutron normally deposits its complete energy in the LENA scintillator volume by multiple scattering processes, which has an effect on the pulse shape. Finally, in LENA the pulse shape discrimination has to be applied at significantly higher visible energies of 10 MeV to 25 MeV in the DSNB detection region.

### 5.1 Simulation Setup

The LENA detector setup is the same as explained in Section 3.3.1. The same scintillation properties as in Section 4.5 are used (see Table 5.1), the Rayleigh scattering and absorption length are set to 20 m for both PXE and LAB and the time resolution of the PMTs is set to 1 ns.

As no experimental data was available for  $N_f$  of  $\alpha$ -particles at higher energies

	PXE	LAB
$ au_f$	$2.9\mathrm{ns}$	3.7 ns
$ au_s$	$29\mathrm{ns}$	$31\mathrm{ns}$
$N_f$	0.8	0.72
$N_f(p,\alpha)$	$0.744 - 0.12 \cdot e^{\frac{-0.00054}{keV} \cdot E_{vis}}$	$0.6895 - 0.086 \cdot e^{\frac{-0.0003}{keV} \cdot E_{vis}}$
$k_b$	$0.15 \mathrm{mm/MeV}$	$0.15 \mathrm{mm/MeV}$

Table 5.1: Scintillation properties for LAB and PXE.  $N_f(p, \alpha)$  denotes the fraction of photons that are emitted by the fast component when an  $\alpha$ -particle or a proton deposites energy,  $N_f$  is applied for all other particles.

in PXE and LAB, it is set to the same energy dependent value as  $N_f$  of protons, which was determined in Section 4.5. This conservative estimate should lead to a smaller discrimination efficiency, as the real value of  $N_f$  is lower for  $\alpha$ -particles than for protons (see Figure 3.14). However, it should have small effect on the average neutron pulse shape, as  $\alpha$ -particles are only created in neutron induced spallation reactions.

A further modification arises by the difference in the time of flight for individual photons. The distance from the origin of a scintillation photon to the PMT where it is finally detected, depends on its initial position and its momentum direction. For example, for a photon that is emitted at a radius of 10 m and z=0 m in the target volume (the z-axis is the symmetry axis of the cylinder, z=0 denotes the center of the cylinder), the shortest distance to a PMT is 5 m and the farthest distance is more than 50 m. This causes a difference in the detection time of two photons that were emitted at the same time, but with a different momentum direction. As the photons are emitted isotropically, this has a great impact on the combined pulse shape recorded by all PMTs (see Figure 5.1). Thus, it is necessary to subtract the so-called time of flight that a photon needs to get from its emission point to its detection point. This is, of course, only possible if there is a precise event position reconstruction method. First Monte Carlo simulations showed that position reconstruction with an uncertainty  $\sigma < 20 \,\mathrm{cm}$  at a visible energy above 10 MeV is possible in LENA [29]. Therefore, for every photon direction the time of flight was calculated with a time jitter of 1 ns (corresponding to  $\sigma \approx 20 \,\mathrm{cm}$  with a refractive index n=1.56), in order to include the uncertainty of the position reconstruction.



Figure 5.1: Comparison of the average pulse shape with (plotted in black) and without (plotted in red) time of flight correction in LENA for a 10 MeV positron at r=10 m and z=0. Without time of flight correction, less photons are detected in the first 10 ns of the events and more afterwards. There is also an additional peak at ~ 100 ns when the photons that were emitted towards the center of LENA are detected on the other side of the steel tank.

### 5.2 Results

The majority of the fast neutrons that reach the target volume from outside will be stopped at a radius of r=10 m or more (see Figure 3.10).

Thus, for all simulated neutrons and positrons the particle origin was set to radius r=10 m and z=0 m, as the fast neutron events are expected at larger radii (see Figure 3.10). The neutron energy was set to 2.3 times the positron energy, as the average neutron quenching factor is 2.3. Neutrons and positrons were simulated at different energies corresponding to an interval of visible energy between 10 MeV and 25 MeV (DSNB energy window see Section 2.2.3). Neutron events can easily be identified, if secondary neutrons are produced, by the additional 2.2 MeV gamma peak from the neutron capture on a proton (see Section 3.7.1). Therefore, neutron events are only included in this analysis, if no secondary neutrons were produced.

As it can take up to a few ns before a neutron generates scintillation light by elastic scattering off protons or inelastic scattering off carbon, the start time of the pulse had to be determined by a constant fraction method. The photon hit times were written into a ROOT histogram with 1 ns binning and the maxinum of entries in a single bin  $N_{max}$  was calculated. The first bin with more than  $0.05 \cdot N_{max}$  entries was considered as the start of the pulse. For the calculation of the tail-to-total ratio, the start of the "tail" interval was set to 15 ns after the beginning of the pulse.

Figure 5.2 shows the tail-to-total ratio of 25000 neutron and 25000 positron events with 10 MeV visible energy in PXE.



Figure 5.2: Tail-to-total ratio of positrons (plotted in red) and neutrons (plotted in black) with 10 MeV visible energy in PXE. With 95% positron acceptance  $99.40 \pm 0.05\%$  of the neutron events can be rejected.

The neutron and the positron peaks are clearly seperated. If 95% of the positron events are accepted,  $99.40 \pm 0.05\%$  of the neutron events can be rejected.

The greater width of the neutron distribution in Figure 5.2 compared to the positron peak has several reasons. As the neutron interacts by varying processes (elastic scattering off protons and inelastic scattering off carbon), the neutron peak is widened due to different secondary particles. Moreover, the neutron deposits its energy in multiple scattering processes. It is possible that several ns pass after the first interaction before the neutron scatters a second time. This leads of course to a greater tail-to-total ratio, as the beginning of the tail interval is set relative to the first scattering process. Hence, the neutron tail-to-total ratio shows an asymmetry to higher values. It is therefore not possible to fit the neutron tail-to-total ratio with a single Gaussian function.

The positron peak also shows a slight asymmetry to higher values. The reason for this characteristic is that the positron will in some cases annihilate with an electron into two gamma quanta before it is stopped. This changes the signal time structure as the gamma quanta need some time to Compton scatter off electrons and thus, the emission of some of the scintillation light is delayed which leads to a higher tail-to-total ratio.

The energy dependence of the neutron-positron discrimination for visible energies between 10 MeV and 25 MeV is shown in Figure 5.3 for both PXE and LAB.



Figure 5.3: Energy dependence of the efficiency of the neutron rejection for PXE (black markers) and LAB (red markers) with 95% positron acceptance.

With 95% positron acceptance, between 99.4% and 99.8% of the neutron events can be rejected in PXE, depending on the visible energy. In LAB, the discrimination efficiency is as expected from the neutron-gamma discrimination in a small detector worse (see Section 4.4), but with 99.0%-99.5% still very good. As expected, the discrimination efficiency in PXE increases with energy, as the measurement of the tail-to-total ratio gets more precise due to the increasing number of scintillation photons. LAB shows a similar energy dependence up to 20 MeV of visible energy, but then the discrimination efficiency starts to decrease. The reason for this effect is that the distance between the positron and the scattered proton peak is still decreasing in LAB, while it is almost constant in PXE at visible energies above 10 MeV (according to the energy dependence of  $N_f(p, \alpha)$  that was determined in Chapter 4, see Table 5.1). Above 20 MeV visible energy, this decrease is not compensated by the increasing number of scintillation photons anymore, which causes the decline of neutron-positron discrimination efficiency. For both LAB and PXE, the efficiency of the neutron-positron discrimination in LENA is lower as the efficiency of the neutron-gamma discrimination at lower energies in a small detector (see Section 4.4). One reason for this is, that by inelastic neutron scattering off carbon, gammas can be emitted, which Compton scatter off electrons and have nearly the same pulse shape as positrons. In LENA all produced gamma quanta will be detected due to the large target mass, while in a small detector the gamma quanta will leave the detector without further interaction.

Another factor which leads to a worse discrimination is the scattering of photons, which is important in LENA due to the large detector dimensions. If a photon is scattered off, its track length between the emission and detection is longer than is it assumed in the calculation of the time of flight and therefore its detection time is increased. Thus, more photons are detected in the tail interval (see Figure 5.4 for a comparison of the average positron pulse shape with 20 m scattering length and a hypothetical scattering length of 20 km in LENA). As photons emitted due to the fast PDF component are now detected in the tail interval originally dominated by the slow component, the efficiency of the neutron positron is decreased. Simulations show that without scattering, the discrimination efficiency at 10 MeV visible energy would increase from 99.40  $\pm 0.05\%$  to 99.85  $\pm 0.03\%$  in PXE.



Figure 5.4: Average pulse shape of 10 MeV positrons in PXE with 20 m scattering length (plotted in black) and a hypothetical scattering length of 20 km (plotted in red), such that the scattering of photons is negligible. If a photon is scattered off, the real track is longer than the assumed one for the time of flight calculation. Thus, more photons are detected in the tail interval after 15 ns for the realistic value of 20 m scattering length than for the hypothetical 20 km scattering length.
#### Chapter 6

## Cosmogenic Background for the DSNB Detection

As only 6 to 13 DSNB events per year are expected in LENA [18], background is a central issue for the DSNB detection. There are three cosmogenic background sources. Muons produce  $\beta n$ -emitting radioisotopes in the scintillator, like <sup>8</sup>He or <sup>9</sup>Li, by spallation reactions on carbon in the scintillator, which have the same signature as  $\bar{\nu}_e$  events. As the detection window for the DSNB is above 10 MeV, due to the reactor  $\bar{\nu}_e$  spectrum, only <sup>9</sup>Li has a large enough Q-value to add to the background. Another source are fast neutrons, because they give a prompt signal due to scattering off protons and carbon, and a delayed signal caused by the neutron capture on a free proton. They are generated by cosmic muons in the surrounding rock and propagate into the detector. Lastly, atmospheric neutrinos provide an intrinsic background and can also produce neutrons by neutral current spallation reactions on carbon in the detector.

In the following analysis, a muon flux of  $\Phi_{\mu}^{L} = 6.5 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1}$  and a mean muon energy of  $\langle E_{\mu}^{L} \rangle = 300 \,\text{GeV}$  is assumed, corresponding to  $4 \,\text{km w.e.}$  shielding [45].

#### 6.1 <sup>9</sup>Li In-situ Production

The maximum energy for the <sup>9</sup>Li- $\beta n$ -decay branch is with 11.3 MeV in the lower end of the DSNB detection region [12]. A shift of the lower threshold above 11.3 MeV would be possible, but is not favorable as the expected DSNB flux is maximal around 10 MeV (see Figure 2.6) and thus, a lot of events would be lost. The cosmogenic <sup>9</sup>Li production rate was measured by the KamLAND experiment. Above 8.3 MeV the observed rate for 1 kt target mass was  $R_{^{9}\text{Li}}^{^{K}} = (2.1 \pm 0.7) \text{ y}^{-1}$  [59]. The production rate depends on the muon flux  $\Phi_{\mu}$ , the mean muon energy  $\langle E_{\mu}^{L} \rangle$  and the number N<sub>12C</sub> of <sup>12</sup>C atoms exposed [60]:

$$R_{^{9}\mathrm{Li}}^{\mathrm{K}} \propto \Phi_{\mu} \cdot \langle E_{\mu} \rangle^{0.75} \cdot \mathrm{N}_{^{12}\mathrm{C}}$$

$$(6.1)$$

Thus, the expected <sup>9</sup>Li production rate in LENA can be scaled from the KamLAND results by the following formula:

$$R_{^{9}\mathrm{Li}}^{\mathrm{L}} = \left(\frac{\Phi_{\mu}^{L}}{\Phi_{\mu}^{K}}\right) \cdot \left(\frac{\langle E_{\mu}^{L} \rangle}{\langle E_{\mu}^{K} \rangle}\right)^{0.75} \cdot \left(\frac{\mathrm{N}_{^{12}\mathrm{C}}^{\mathrm{L}}}{\mathrm{N}_{^{12}\mathrm{C}}^{\mathrm{K}}}\right) \cdot R_{^{9}\mathrm{Li}}^{\mathrm{K}}$$
(6.2)

The mean muon flux in KamLAND is  $\Phi^{\rm K}_{\mu} = (1.70 \pm 0.05) \cdot 10^{-3} {\rm m}^{-2} {\rm s}^{-1}$ , the mean muon energy is  $\langle E^{K}_{\mu} \rangle = (268 \pm 2) {\rm GeV}$  [61] and  ${\rm N}^{\rm K}_{^{12}{\rm C}} = 4.4 \cdot 10^{31}$ . If the radius of the fiducial volume is set to 12 m in LENA,  ${\rm N}^{\rm L}_{^{12}{\rm C}} = 2.0 \cdot 10^{33}$  for PXE and  ${\rm N}^{\rm L}_{^{12}{\rm C}} = 1.7 \cdot 10^{33}$  for LAB.

The resulting <sup>9</sup>Li background rate is  $R_{^{9}\text{Li}}^{^{1}} = (4.1 \pm 1.4) \text{ y}^{-1}$  in PXE and  $R_{^{9}\text{Li}}^{^{1}} = (3.4 \pm 1.1) \text{ y}^{-1}$  in LAB. Thus, for both scintillators the <sup>9</sup>Li background is in the same order of magnitude as the expected DSNB signal. However, the production of <sup>9</sup>Li is caused by a cosmic muon crossing the scintillator and the half-life of <sup>9</sup>Li is  $T_{1/2} = 0.18 \text{ s}$ , the <sup>9</sup>Li background can be reduced to about  $R_{^{9}\text{Li}}^{^{1}} = (0.08 \pm 0.03) \text{ y}^{-1}$  for PXE and  $R_{^{9}\text{Li}}^{^{1}} = (0.07 \pm 0.02) \text{ y}^{-1}$  for LAB, if the detector is vetoed for 1 s after each muon. The muon crossing rate is  $210 \text{ h}^{-1}$ , therefore the introduced dead time will correspond to ~ 6% of the measuring time. Because <sup>9</sup>Li is produced close to the muon track, it is possible to reduce the dead time to about ~ 0.1%, if only a cylinder with 2 m radius around the muon track is vetoed.

#### 6.2 Muon-induced Neutrons

The fast neutron background rate in LENA was determined by a Monte Carlo simulation (see Chapter 3) in the frame of this thesis. One way to reduce this background is to exclude events that have more than one neutron capture signal within 1 ms, because fast neutrons can produce secondary neutrons (see Section 3.7.1). Since neutrons have a different typical pulse shape than positrons that are generated in the inverse beta decay reaction, a further reduction is possible by pulse shape discrimination between neutron and  $\bar{\nu}_e$  events (see Chapter 5). The resulting background rates for 10 years measuring time in the DSNB detection region for PXE and LAB are shown in Table 6.1 and Figure 6.1.

If the fiducial volume radius is set to 12 m, about 1.2 neutron background events are expected for 10 years measuring time in LAB. Due to the higher

Fiducial Volume	Neutron ba	utron background [/10 yrs] Expected	
Radius [m]	for PXE	for LAB	DSNB-signal [/10 yrs]
13	3.0	6.2	67-145
12.5	1.5	3.1	62-134
12	0.5	1.2	57-124
11.5	0.2	0.5	52-113
11	0.1	0.2	48-104

Table 6.1: Fast Neutron background rates in the DSNB detection region after 10 years measuring time as a function of the fiducial volume radius in LENA. The multiple neutron capture cut (see Section 3.7.1) and the pulse shape discrimination cut (see Chapter 5) were applied. For comparison, the expected DSNB signal is also denoted.

self-shielding effect and the better discrimination between neutron and  $\bar{\nu}_e$  events, only 0.5 neutron background events are expected in PXE in the same time span. Thus, a high signal to background ratio can be achieved for both scintillators, without losing too much target volume.

In the pre-design study for LENA at the Pyhäsalmi location the external water Čerenkov muon veto will have an elliptical shape with a minimum thickness of 2 m shielding. Compared to the Monte Carlo study presented here, this would result in a larger effective shielding. In this case, the fast neutron background would be reduced and it should be possible to set the fiducial volume radius to 13 m, which would enlarge the target volume by  $\sim 17\%$ .

#### 6.3 Atmospheric Neutrinos

Atmospheric electron antineutrinos provide an intrinsic background (see Section 2.2.3), of ~ 0.5 events per year in the DSNB detection region [12]. However, it is possible that an atmospheric neutrino of higher energy knocks out a neutron from a <sup>12</sup>C atom by a neutral current interaction:

$$\nu_x + {}^{12}\text{C} \to \nu_x + {}^{11}\text{C}^{(*)} + n$$
 (6.3)

The knocked out neutron mimics the same delayed coincidence signal as the inverse beta decay reaction, and the expected background is with  $\sim 82$  events per year in the DSNB detection window about one order of magnitude larger than the expected DSNB signal [62] (see Figure 6.2).



Figure 6.1: Fast Neutron background rates in the DSNB detection region after 10 years measuring time as a function of the fiducial volume radius in LENA for PXE (plotted in black) and LAB (plotted in red). The multiple neutron capture cut (see Section 3.7.1) and the pulse shape discrimination cut (see Chapter 5) were applied. Due to the higher discrimination efficiency and self-shielding effect, the fast neutron background rate is less in PXE than in LAB.



Figure 6.2: The expected atmospheric neutral current neutrino background in LENA (plotted in red) after 10 years measuring time [62]. For comparison, the expected DSNB-signal according to the KRJ-model [32] is shown (plotted in blue).



Figure 6.3: Occupation of the <sup>11</sup>C energy levels in the the simple shell model, with one hole in the  $S_{1/2}$  shell [63]. The energy difference between the  $P_3/2$  and the  $S_1/2$  state is larger than separation energy for nucleons. Thus, the <sup>11</sup>C will deexcitate mainly by the emission of protons, neutrons, or  $\alpha$ -particles [63].

A first approach to reduce this background is to search for the decay of the produced  $^{11}\mathrm{C}$  atom.

However, the <sup>11</sup>C isotope is produced in the ground state only two thirds of the time, in case that one of the four neutrons of the P<sub>3/2</sub> shell is knocked out by the atmospheric neutrino [63]. One third of the time, the knock-out neutron is one of the two neutrons of the S<sub>1/2</sub> shell and the resulting <sup>11</sup>C atom is in an excited state (see Figure 6.3). As the excitation energy of the <sup>11</sup>C\* atom exceeds with ~ 23 MeV the separation energy of nucleons in <sup>11</sup>C, the nucleus will mainly deexcitate via the emission of protons, neutrons, or even  $\alpha$ -particles [63]. The deexcitation by neutron emission happens 15% of the time and can be identified by the additional 2.2 MeV signal from the neutron capture on a proton. In the other case, the signal from the emitted protons and  $\alpha$ -particles can not be identified as is it superimposed with the prompt signal from the knocked out neutron. The residual daughter nucleii are either stable or have a halflife of ~ 50 d or more. Thus, a direct identification of the deexcitation products is not possible.

The  $\beta^+$ -decay of <sup>11</sup>C has a half-life of 20 min and deposits between 1 MeV and 2 MeV in the scintillator. It should therefore be well above background, allowing to reject two thirds of the neutral current atmospheric events by vetoing on the coincidence with the initial neutron signal. If a neutron is knocked out of a <sup>12</sup>C atom, the mean free distance between the reconstructed neutron and the <sup>12</sup>C position is ~ 18 cm [28]. Thus, a 1 m radial cut around a potential DSNB-event for 5 times the half-life of <sup>11</sup>C should be sufficient to identify ~ 95% of the <sup>11</sup>C decays. If also the multiple neutron capture cut is applied, ~ 68% of the atmospheric neutral current neutrino background can be identified.

As <sup>11</sup>C is also produced by spallation from cosmic muons, it is possible that a DSNB event is misidentified as background by random coincidence. The BOREXINO experiment measures 26 <sup>11</sup>C  $\beta^-$  decay like events per day in 100 t of liquid scintillator [28]. This rate is reduced by a factor of ~ 5 in LENA, due to the lower muon flux. Thus, about 2% of the DSNB-events are misidentified and therefore lost.

A further reduction of the background is possible by the application pulse shape discrimination as it has been demonstrated for the fast neutron background. In PXE about 99.4% and in LAB about 99.0% of the neutron events can be identified by this method (see Section 5.2). Thus, the remaining background is reduced to  $\sim 1.5$  events in PXE and  $\sim 2.5$  events in LAB for 10 years measuring time (see Figure 6.4). As this is about 1-2 orders of magnitude less than the expected DSNB-signal (57-124 events per 10 yrs), none of the cosmogenic background seriously endangers the detection of the DSNB in LENA.



Figure 6.4: The expected background from neutral current reactions of atmospheric neutrinos in LENA after 10 years measuring time [62], with all background identification cuts applied for PXE (plotted in black) and LAB (plotted in red). For comparison, the expected DSNB-signal according to the KRJ-model is also shown (plotted in blue).

#### Chapter 7

### **Conclusions and Outlook**

The proposed LENA detector has a great potential for the detection of rare  $\bar{\nu}_e$  events like the diffuse supernova neutrino background (DSNB). Present day Water Čerenkov detectors like Super-Kamiokande are only able to set upper limits on the DSNB flux. Due to its large target mass of about 50 kt and the superior background discrimination of a liquid-scintillator detector, about 60-130 DSNB events will be identified in LENA after 10 years measuring time. As this rate is still low, background is a crucial issue for the DSNB detection, even in a liquid-scintillator detector. Reactor  $\bar{\nu}_e$  and atmospheric  $\bar{\nu}_e$  provide an indistinguishable background and limit the detection region to about 10 MeV to 25 MeV, exact upper and lower limit depending on the detector site. Another important background source are fast neutrons that are produced by cosmic muons in the surrounding rock and that propagate into the detector, where they cause the same delayed coincidence signal as  $\bar{\nu}_e$  events.

In the present work, a GEANT4-based Monte Carlo simulation of this background was performed. In a first step the neutron production in the rock was simulated. At a depth of 4 km w.e. shielding, a muon that passes the rock next to the detector produces on average ~ 12 neutrons for 100 m track length. Out of them, 2.9 feature energies of 40 MeV or higher, which was determined by simulations to be the minimum required for reaching the target volume. These rates are in good agreement with similar simulations based on the FLUKA code [45]. The simulated initial energy spectrum and angular distribution were used as input values for the simulation of the neutron propagation into the detector.

For both investigated scintillators, PXE and LAB, the fast neutron background rate in the geoneutrino detection window was below 10 events per year and is therefore insignificant compared to the  $\sim 1000$  expected geoneutrino events. In the DSNB detection window, about 70 fast neutron events per year are expected in PXE and about 80 per year in LAB. This background can be reduced by a fiducial volume cut. In order to achieve a signal background ratio of about 10:1, a minimum shielding of about 7 m w.e. is needed. In the present setup of LENA this would reduce the target volume by about 40%. One method to suppress this background is to exclude events with more than one neutron capture signal within 1 ms, as fast neutrons can generate secondary neutrons, contrary to  $\bar{\nu}_e$  events. With this method, about 30% to 40% of the fast neutron events in the DSNB detection window can be identified.

As proton recoils of neutrons feature a different pulse shape than positrons generated in the inverse beta decay reaction, it is possible to identify neutron events by pulse shape analysis. To obtain the necessary input parameters of the signal shapes, a laboraty experiment using a small scintillator cell and a Am-Be neutron source was performed. Neutron-induced proton- and gamma-induced electron recoils in the cell were analyzed. For PXE (with  $10\frac{g}{1}$  PPO), over 99.9% and for LAB (with  $10\frac{g}{1}$  PPO) over 99% of the neutron events with an visible energy between 2 MeV and 3.5 MeV could be identified, if 97.8% of the gamma events were accepted.

Based on the experimental values, the efficiency of the pulse shape discrimination between neuton and  $\bar{\nu}_e$  events at visible energies between 10 MeV and 25 MeV was analyzed by a Monte Carlo simulation of LENA. In PXE over 99.4% and in LAB over 99.0% of the neutron events could be identified, while still accepting 95% of the  $\bar{\nu}_e$  events. As the pulse shape discrimination was measured at low energies, the probability density functions (PDF) of the scintillation process for the positron and the recoil protons had to be extrapolated to the DSNB detection window.

In order to reduce the systematic uncertainties that are generated by this extrapolation, a measurement of the neutron pulse shape at energies above 10 MeV should be performed. The laboratory experiment should be repeated with smaller PPO concentrations in the samples. The aspired PPO concentration is about  $2\frac{g}{1}$  to avoid self-absorption processes of the wavelength shifter [15].

Applying all background suppression cuts and setting the fiducial volume radius to 12 m, the expected fast neutron background rate for the DSNB detection in LENA is about 0.5 fast neutron events in 10 years for PXE and about 1.2 for LAB. As only 95% of the  $\bar{\nu}_e$  events are accepted due to the pulse shape discrimination, the expected DSNB signal is slightly reduced to 57-124 events per 10 years.

Two further cosmogenic background sourced were investigated. <sup>9</sup>Li that is produced in the liquid scintillator by cosmic muon spallations features a  $\beta n$ 

decay that mimics the  $\bar{\nu}_e$  signals. If a cylinder of 2 m radius around each crossing muon is vetoed for 1 s, the background rate to the DSNB can be reduced to 0.7-0.8 events per 10 years measuring time.

Another background is caused by atmospheric neutrinos that knock out neutrons from <sup>12</sup>C atoms by neutral current reactions. As about 820 events in 10 years are expected, it is crucial for the DSNB detection to reduce this background. One way to do this, is to search for the  $\beta^-$  decay of <sup>11</sup>C in its ground state, which is produced two thirds of the time, and for additional neutrons from excited <sup>11</sup>C, which are emitted 5% of the time. Due to random coincidences, this will cause a small reduction of the expected DSNB signal to 56-121 events per 10 years. As all other decay channels of <sup>11</sup>C<sup>\*</sup> can not be vetoed by coincidence with a delayed particle, the pulse shape discrimination has to be used to reduce the background further to about 1.5 events for PXE and to about 2.5 for LAB per 10 years measuring time.

It is evident that the cosmogenic background exceed the expected DSNB signal without any background suppression cuts. While the fast neutron background can be reduced with an increase of the water shielding around the buffer or a decrease of the fiducial volume radius to 10 m, the only way to reduce the background from neutral current reactions of atmospheric neutrinos is to perform the pulse shape discrimination of neutron and  $\bar{\nu}_e$  events. Experimental results at low visible energies between 2 MeV and 3.5 MeV in a small scintillator cell and the simulation of the neutron-positron pulse shape discrimination in the DSNB detection region in LENA demonstrated the great potential of this method. Based on the results of the present work, a detection of the DSNB with a signal to background ratio of about 10:1 or better is achievable with both PXE and LAB in LENA.

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