INVESTIGATION OF THE MUON BACKGROUND FOR THE NEMENIX PROTOTYPE OF THE SOLID EXPERIMENT

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Neutrino’s behoren momenteel tot de populairste deeltjes in de wereld van de elementaire deeltjesfysica. Gezien er nog veel te ontdekken valt omtrent hun eigenschappen en gedrag, kunnen ze beschouwd worden als een van de meest intrigerende onderwerpen voor experimenteel onderzoek. Anderzijds, omdat ze enkel zwak interageren met andere materie, is het bijzonder uitdagend gebleken om deze deeltjes te detecteren en te bestuderen.

Over de voorbije decennia hebben theoretici zoals Pauli, Fermi, Pontecorvo en vele anderen het pad van neutrino fysica geopend en verkend. Uit een brede waaier van neutrino experimenten volgde geleidelijk aan de bevestiging van theoretische concepten. Tegen de jaren ’80 van de vorige eeuw werd het beeld van 3 neutrino’s, die in mekaar kunnen transformeren via smaak oscillaties, de algemeen geaccepteerde standaard. Verschillende, meer recente, experimenten lijken het 3-neutrino model echter aan wanke len te brengen. Zowel versneller experimenten, als opstellingen bij nucleaire reactoren en ook calibratie metingen die gebruik maken van radioactieve bronnen, tonen onverwachte tekorten of excessen aan neutrinos, die met het huidige model niet verklaard kunnen worden. Deze inconsistencies ten opzichte van het 3-neutrino plaatje worden de neutrino anomalieën genoemd.

Indien nieuwe experimenten de bestaande anomalieën bevestigen, dan zullen neutrino’s de eerste deeltjes zijn die fysica vertonen die volledig buiten het Standaard Model valt. Een mogelijke verklaring van de anomalieën zou namelijk te vinden zijn in een vierde type, steriel neutrino, dat enkel onderhevig is aan de zwaartekracht.

Hoofdstuk 1 van deze thesis behandelt de theoretische en experimentele mijlpalen uit de geschiedenis van de neutrino fysica. Ook de recentere ontwikkelingen met betrekking tot de anomalieën en de mogelijke oplossing van het steriele neutrino worden besproken.

Een van de experimenten die een verdere test van de neutrino anomalieën kan voorzien en mogelijk het bestaan van het steriele neutrino kan bevestigen, is het SoLid experiment. Dit recent ontwikkelde project werd ontworpen om de reactor anti-neutrino anomalie te
onderzoeken op zeer korte reactor-detector afstanden. De SoLid detector maakt gebruik van scintillator materiaal om de reactor anti-neutrino’s te detecteren via een invers beta verval. De experimentele opstelling staat bij de BR2 reactor op de site van het SCK•CEN in Mol, België.

Om een eerste evaluatie van de detectorwerking en -efficiëntie mogelijk te maken werd een kleinschalig prototype gebouwd van de SoLid detector. Dit prototype, NEMENIX genaamd, werd voor het eerst bij BR2 geïnstalleerd in de zomer van 2013. De gegevens die door dit prototype werden verworven hebben de collaboratie voorzien van informatie die nuttig was voor de verdere ontwikkeling van het SoLid experiment.

In december 2014 is een eerste grootschalige module van de SoLid detector bij de BR2 reactor geplaatst. Kort geleden werd de eerste cyclus van metingen met deze module afgerond. De analyse van deze data is momenteel, mei 2015, nog volop bezig.

Het werkingsprincipe van de SoLid detector en de structuur en compositie van het NEMENIX prototype worden in meer detail besproken in hoofdstuk 2.

Zoals dat het geval is voor vele experimenten in de deeltjesfysica, vormen kosmische muonen ook voor het SoLid experiment een grote bijdrage tot de ongewenste achtergrond. Het doel van deze thesis is om inzicht te verwerven in de mogelijke interacties van deze energetische deeltjes met de NEMENIX detector. Het onderzoek werd bijgevolg toege- spitst op de elektronische respons van het NEMENIX prototype op de energiedepositie van de kosmische muonen. Voor de analyse van de signalen van kosmische muonen werd een C++ code geschreven, die later ook geïmplementeerd werd in een nieuw framework voor gemeenschappelijke analyses. De code en zijn structuur worden besproken in hoofdstuk 3.

Met dit werk werden de eerste stappen genomen in de richting van een algemene definitie voor de experimentele achtergrond, veroorzaakt door kosmische muonen. De effecten die de muonen veroorzaken kunnen opgedeeld worden in verschillende gevallen. Voor deze thesis werden enkele van die specifieke gevallen, die verwacht worden vrij frequent voor te komen, geselecteerd en bestudeerd. De resultaten hiervan worden gepresenteerd in hoofdstuk 4.
Introduction

Neutrinos are becoming very popular in the world of particle physics. Because there is still a lot to find out about the properties and behaviour of neutrinos, they form one of the most interesting topics for experimental investigations. On the other hand, since they interact only weakly with matter, it has proven to be particularly challenging to detect and study these particles.

Over the past decades, theorists such as Pauli, Fermi, Pontecorvo and many others opened and explored the path of neutrino physics. A confirmation of the theoretical concepts was found step by step, by a diverse range of neutrino experiments. By the 1980s, the picture of three neutrinos which can transform into each other by flavour oscillations, became the generally accepted standard.

More recently, however, different types of oscillation experiments seem to push the barriers of the neutrino physics outside the well-established framework of 3 neutrinos. Accelerator experiments, as well as nuclear reactor experiments and calibration measurements with radioactive sources, all show deficits or excesses of neutrinos, which are so far unexplained. These inconsistencies with the 3-neutrino model are known as the neutrino anomalies.

If new experiments confirm the anomalies, neutrinos will be the first particles that really show physics beyond the Standard Model. Indeed, one possible explanation of the anomalies involves a fourth and sterile neutrino, which is only subject to the fundamental force of gravity.

Chapter 1 of this thesis will deal with the theoretical and experimental milestones of the history of neutrinos. Also the more recent developments concerning the anomalies and the possible solution of the sterile neutrino will be discussed.

One of the experiments that can do an extended test of the neutrino anomalies and might confirm the existence of the sterile neutrino, is the SoLid experiment. This newly developed project is designed to evaluate the reactor antineutrino anomaly at very short reactor-detector baselines. The SoLid detector uses scintillator material to detect the
reactor antineutrinos via an inverse beta decay interaction. The experimental set up is located at the BR2 reactor site of the SCK•CEN in Mol, Belgium.

As a proof of principle and to have a first evaluation of the detector response and efficiencies, a small-scale prototype of the SoLid detector was built. This prototype, called NEMENIX, was first deployed at BR2 in the summer of 2013. The experimental data gathered by NEMENIX provided the collaboration with valuable information for the further development of the SoLid experiment.

In December 2014, a first large-scale submodule of the SoLid detector was placed at the BR2 site. Recently, the first stage of data-taking with this detector module was completed. The data analysis for this cycle is currently, May 2015, ongoing. The working principle of the SoLid detector and the structure of the NEMENIX prototype are explained in more detail in chapter 2.

As is the case for a lot of particle physics experiments, cosmic muons give a large contribution to the background of the SoLid experiment. The goal of this thesis is to gain some understanding of the possible interactions of these muons with the NEMENIX detector. Therefore, an investigation of the NEMENIX response to cosmic muon background was performed. For the analysis of the cosmic muon signatures, a C++ code was written and implemented in a new analysis framework structure, as will be discussed in chapter 3.

In the course of this work, the first steps were taken towards a global definition of the cosmic muon background. The effects of the muon background can be split up in different types of so-called events in the detector. For this thesis, those types of cosmic muon events which are expected to occur most frequently, were reconstructed and analyzed, the results of which are presented in chapter 4.
Chapter 1

Neutrino Physics

1.1 The Standard Model

The Standard Model of elementary particle physics is designed to bundle all known elementary particles and to define how these interact with each other. Therefore, it is also referred to as the Standard Model of fundamental interactions. The development of this model started with the attempt to unify the electroweak theory, which itself is a unification of the mathematics describing electromagnetism and those explaining the weak force, and the theory of quantum chromodynamics (QCD), which describes the strong nuclear force. This theoretical framework was cast in its final form in the mid-1970s, comprising three of the four known fundamental forces; the electromagnetic force and the weak and strong nuclear forces. The fourth force, gravity, is not included in the Standard Model. The lack of a theory unifying all four forces, often solemnly referred to as the Theory of Everything, is one of the biggest unsolved problems in theoretical physics. For the study of elementary particles, however, gravity is of so little effect that this force can be neglected in almost every particle physics experiment. Table 1.1 shows the four interactions with their typical strength\(^1\), the particles through which they interact and their signature charges.

The fundamental forces of the Standard Model are mediated by gauge bosons, which are integer spin particles. A photon is exchanged when particles interact via the electromagnetic force, W- and Z-bosons are the exchange particles of the weak force and the strong force is driven by gluon-exchange.

\(^1\)The values given for the relative strength are approximate and indicate the order of magnitude, rather than an exact value; they depend on the kind of particles and their energies and are related to the coupling constant of the force in its describing quantum field theory.
Table 1.1: The four fundamental forces. [1]

<table>
<thead>
<tr>
<th>Force</th>
<th>Relative Strength</th>
<th>Gauge bosons</th>
<th>Couples to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>1</td>
<td>photon (γ)</td>
<td>electric charge</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-10}$</td>
<td>$W^\pm, Z^0$</td>
<td>weak charge</td>
</tr>
<tr>
<td>Strong</td>
<td>100</td>
<td>8 gluons</td>
<td>colour charge</td>
</tr>
<tr>
<td>Gravitation</td>
<td>$10^{-40}$</td>
<td>graviton</td>
<td>mass</td>
</tr>
</tbody>
</table>

Apart from these exchange bosons, the model also includes another group of elementary particles, which are all fermions with half-integer spin. This group contains the leptons and the quarks. They are divided into three so-called families or generations, based on their respective masses. Table 1.2 gives an overview. Each fermion in this table has a corresponding anti-fermion with the same mass and lifetime, but with opposite sign for the different charges.

The three lepton families are referred to by $e$, $\mu$ and $\tau$. Each of them is represented by an electromagnetically charged lepton and a neutral lepton, called neutrino. The leptons do not carry colour charge and they are therefore no subject to the strong interaction. The weak force divides each family into a left-handed doublet, with weak isospin $1/2$, and a right-handed singlet, with weak isospin 0. The isospin doublets consist of a neutrino and a charged lepton. The components of a doublet differ by one unit of electric charge and they can transform into each other by emitting or absorbing a W-boson. The right-handed fermions, however, do not couple to the W-bosons and can only interact via Z-boson exchange. Within the Standard Model neutrinos can only be left-handed. Their anti-particles, the antineutrinos, are thus always right-handed.

The three quark families each have an up-type quark and a down-type quark. Ordered by increasing mass the combinations are; up and down, charm and strange and top and bottom. The quarks do have a colour charge (red, blue or green) and thus interact strongly via the exchange of the coloured gluons. They also make up some weak isospin multiplets, like the leptons. All quarks, in contrast with the neutral leptons, can exist in both left-handed and right-handed states.

Leptons and quarks are considered to be point-like particles, without any substructure. They are thus the fundamental building blocks of matter. Moreover, because of the strong interaction, quarks can never exist as free particles. Instead they are confined in colour-neutral or white combinations. These can be formed by combining three quarks of a different colour or by canceling out a colour with its anti-colour in a combination of two quarks. The subatomic particles that exist of a combination of quarks are called

---

2There are 13 in total. The recently discovered Higgs boson is also one of them.

3Examples of colour neutralization are; \( \text{red} + \text{blue} + \text{green} = \text{white} \) or \( \text{red} + \text{anti-red} = \text{white} \).
Table 1.2: Fermions; the building blocks of matter.

<table>
<thead>
<tr>
<th>Family</th>
<th>Electric charge</th>
<th>Weak Isospin Multiplets</th>
<th>Weak Isospin</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>( \nu_e, \nu_\mu, \nu_\tau )</td>
<td>1/2</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>( e, \mu, \tau )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>+2/3</td>
<td>( u, d, s, b )</td>
<td>1/2</td>
<td>0</td>
</tr>
</tbody>
</table>

Leptons

Quarks

\[ \begin{array}{c}
1/2 \quad 0 \\
0 \quad 1/2 \\
-1 \quad 0 \\
+2/3 \quad 0 \\
-1/3 \quad 0 \\
\end{array} \]
hadrons. Protons and neutrons, together known as the nucleons, are part of the subclass of the hadrons which contains the particles characterized by three valence quarks. This class is referred to by the term baryons. The proton is the combination of two up quarks and one down quark (uud), the neutron has one up and two down quarks (udd). The other subclass of the hadrons are the mesons, having two valence quarks. Examples of these are the pions (ud) and the kaons (us). The many possible combinations of quarks lead to a large number of possible composite particles, many of which were actually discovered before the concept of quarks was introduced. The great amount of known hadrons is sometimes referred to as the particle zoo.

1.2 Neutrinos in the Standard Model

From table 1.2 it can be seen that the neutrino is somewhat different from the other fermions: it does not interact electromagnetically, it does not interact via the strong force and it only has a left-handed component within the weak interaction. These limits on its interacting possibilities make it very difficult to detect a neutrino, which in turn makes it even harder to study the properties of this elusive particle.

1.2.1 Theoretical evidence

The theoretical birth of the neutrino is closely linked to the developments in the description and study of beta decay in the first decades of the 20th century. The process of beta decay describes the radioactive decay of an atomic nucleus \((A, Z)\) to a lighter one \((A, Z + 1)\) by the emission of an electron. This basically is equal to the conversion of a neutron to a proton inside the nucleus:

\[
    n \rightarrow p + e^-.
\]  

(1.1)

The laws of momentum and energy conservation state that for a two body decay like this, both particles should have a fixed energy. These two particle energies sum up to the so-called Q-value of the reaction, which is related to the mass difference between the original nucleus and the reaction products:

\[
    Q = M(A, Z) - M(A, Z + 1) - m_e^-.
\]  

(1.2)

The proton is confined in the nucleus and will (approximately) stay at rest in this decay, therefore leaving all energy to the much lighter electron which escapes. Experiments conducted in the 1920s showed that the electron energy spectrum was not compatible
with the assumed fixed Q-value. Instead, they resulted in a continuous energy spectrum, with electron energies ranging from zero to very close to the Q-value.

![Figure 1.1: The expected and observed energy spectra for the electron in a β-decay.][2]

For a few years this result seemed inexplicable and it even raised doubt about the laws of conservation of energy and momentum. In 1930, the Austrian physicist Wolfgang Pauli wrote his famous letter in which he gave a solution to the problem. He stated that, besides the electron, a second light particle was emitted in this reaction. The released energy could thus be split over these two particles, leading to a spectrum as seen in the experiments.

This second particle could only be neutral, otherwise it would already have been detected in the experiments. The particle would also be very light, since the maximal electron energy in the spectrum did not deviate much from the Q-value calculated from equation 1.2. At that time there were no known particles that could fit these requirements, so Pauli stated that a new and unknown particle had to be involved. However, it was not Pauli, but the Italian physicist Enrico Fermi who created a fully comprehensive theory of beta decay and it was he who baptized the new particle neutrino.

### 1.2.2 Experimental evidence

Although the neutrino became a well accepted particle with Fermi’s ground-breaking theory, its existence still had to be verified experimentally. Because estimates of the neutrino-nucleus cross-section gave an upper bound that was extremely small\(^4\), a lot

\(^4\)Soon after Fermi had published his theory, Bethe and Peierls made a first estimation of the cross section (\(\sigma\)) of the process \(\bar{\nu}_e + (A, Z) \rightarrow e^+ + (A, Z - 1)\). They found that \(\sigma < 10^{-44}\) cm\(^2\) [3].
of physicists, and even Pauli himself, worried that he had postulated a particle which would never be detected.

Since the interaction cross-section of a neutrino is so low, the only option to increase the chance of a neutrino interacting with a detector is to have a very high flux of neutrinos and a very large amount of detector material. A good source of neutrinos is a nuclear fission environment. In a nuclear fission process, a heavy nucleus splits into two neutron-rich daughter nuclei. Their large excess of neutrons makes these resulting nuclei highly unstable and they will undergo consecutive $\beta$-decays to transform some of their neutrons into protons. In these beta decay cascades, a lot of antineutrinos are produced.

Some researches who had been working at the Los Alamos site during the Second World War, later wondered whether their gathered expertise in nuclear explosions could be used to advance the insights in fundamental physics. The physicists Clyde Cowan and Frederick Reines believed that an atomic bomb explosion was the best neutrino source for a first attempt to detect these, up to then, elusive particles. The detection process of their choice was an inverse beta decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

in which an antineutrino interacts with a proton of an organic scintillator volume. The positron and, with some time delay, the neutron would produce a light signal in the detector. While investigating the detector signal, Cowan and Reines suddenly realized that this specific signal would be so good at differentiating the event from background signals that also a nuclear fission reactor, instead of a nuclear bomb, would suffice as neutrino source. This new inspiration made the experiment much more feasible.

The experiment started off at Hanford, but due to a too high cosmic background the results were very poor. The detector set-up was then moved to the more powerful Savannah River reactor, where the experiment could take place underground. The higher neutrino flux, the much better shielding from backgrounds and an increased neutron sensitivity eventually led to the first experimental evidence of the neutrino. About forty years later, in 1995, Reines was rewarded with the Nobel Prize for this extraordinary work [4].

1.2.3 Further developments

A next step in the evolution of neutrino physics was the discovery of the muon neutrino ($\nu_\mu$) by L.M. Lederman and his co-workers [5]. In 1962, they conducted an experiment to

---

5His companion Clyde Cowan passed away in 1974.
verify whether neutrinos produced in reactions that involve muons are different from the neutrinos that are created in association with electrons and positrons. The experiment was based on the decay of pions

\[ \pi \rightarrow \mu + \nu_\mu. \]  

(1.4)

These pions were obtained by letting an energetic proton beam impinge on a beryllium target. The proton beam was generated by the newly built Alternating Gradient Synchrotron (AGS) in the Brookhaven National Laboratory. If the neutrinos produced in the \(\pi\)-decay were equal to the ones produced in \(\beta\)-decay, it should be possible to convert them into electrons. The experiment found, however, that only muons were produced by these neutrinos. Therefore it was proven that the electron neutrino \(\nu_e\) and muon neutrino \(\nu_\mu\) are different particles.

The discovery of the muon neutrino unraveled the structure of the leptons, which seemed to form doublets of a charged lepton associated with a neutrino. The question was raised whether other, sequential leptons existed and if so, how much. The first part was answered in 1977, when M. Perl et. al. discovered the \(\tau\)-lepton at the electron-positron collider at Stanford [6]. To comply with the Standard Model, that was already in excellent shape by then, the existence of the \(\tau\)-lepton required the existence of a third neutrino, the \(\nu_\tau\). It took another 23 years before this third neutrino was first observed by the DONUT Collaboration at Fermilab [7].

The question on the number of lepton families was tackled by the LEP experiment, measuring the decay of the Z-boson [8]. The number of decay channels that are available for the Z-boson, influences the lifetime and thus the width of the Z-resonance. Every additional decay channel of the type

\[ Z \rightarrow \nu_\ell + \bar{\nu}_\ell \]  

(1.5)

makes the total width of the resonance larger by some hundreds of MeV. It can be seen from figure 1.2 that a value \(N_\nu = 3\) complies best with the experimental results. Following the Standard Model, this constraint on the number of neutrino families also implies that there exist no more and no less than three lepton families.

### 1.3 Neutrinos beyond the Standard Model

While it has proven to be extremely successful in describing most of the concepts in particle physics, the Standard Model seems to fail when it comes to the explanation of observations involving neutrinos. The Standard Model picture of three distinct types
Chapter 1. Neutrino Physics

1.3.1 Solar and Atmospheric Neutrino Experiments

In the late 1960s American chemist Ray Davis set up an experiment to measure the flux of electron neutrinos coming from the Sun. He used a radiochemical detection method in which the reaction

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Al} + e^-$$

was observed. The results of this first solar neutrino experiment were compared with theoretical predictions of the Standard Solar Model (SSM), which gave a description of the chain of reactions that burn up the Sun. It appeared that Davis detected only $1/3$ of the predicted neutrino flux. This inconsistency created the solar neutrino problem.

Since it was hard to make accurate and indisputable calculations for the processes in the Sun, the solar neutrino problem could be due to flaws in the SSM theory. It could also emanate from a misunderstanding of the detection principles or efficiency. And just as well could it be evidence for new physics. The problem was not easy to tackle.

When other solar neutrino experiments were performed in the eighties (Kamiokande II [9]) and nineties (GALLEX [10] and SAGE [11]), their measured fluxes again did not comply with the SSM predictions. These observations thus confirmed the solar neutrino problem and ruled out the idea that Davis’ experiment was wrongly interpreted.
A similar problem arose in the study of atmospheric neutrinos. When energetic cosmic particles, mostly protons, interact with the Earth’s atmosphere they create a lot of pions. The pions decay into muons within the upper layers of the atmosphere. These so-called cosmic muons mostly travel a large part of the atmosphere before they decay into electrons. In both decays, neutrinos are produced in the reactions

\[ \pi \rightarrow \mu + \nu_\mu \]
\[ \mu \rightarrow e + \nu_e + \nu_\mu. \]  

(1.7)

From these equations one can see that the expected ratio of muon neutrinos to electron neutrinos is 2:1. Experiments measuring the flux of muon neutrinos in relation to the flux of electron neutrinos (Kamiokande, IMB) could not confirm this ratio, but instead pointed to a much lower ratio which indicated that the actual flux of muon neutrinos was lower than theory predicted. The number of indications in favor of new physics continued to grow.

The deficit of muon neutrinos from the atmosphere (atmospheric neutrino anomaly) and the too low number of electron neutrinos coming from the Sun (solar neutrino problem) were the first experimental indications of neutrino flavour oscillations. More striking evidence was seen in the results of Super-Kamiokande, published in 1998 [12]. This experiment captured atmospheric muon neutrinos in a large water Cherenkov detector. The measured distribution of muon neutrinos seemed to vary enormously over different zenith angles. From figure 1.3 (left) it can be seen that the zenith angle is related to the distance travelled between the point of creation in the atmosphere and the point of detection of the muon neutrinos. Figure 1.3 (right) shows that there are less muon neutrinos entering the detector from below than from above. The ones entering from above, with a small zenith angle, travel a shorter distance since they only have to traverse the Earth’s atmosphere, the ones entering from below travel a significantly larger distance, since they have to traverse both the atmosphere and the Earth itself.

### 1.3.2 Theory of neutrino oscillations

The first idea of neutrino oscillations was suggested by Bruno Pontecorvo in 1957, which was years before there was any experimental evidence of oscillations and even of multiple neutrino flavours. He was inspired by the then recent experimental evidence of kaon-mixing \( K^0 \leftrightarrow \bar{K}^0 \) in the quark-sector. Pontecorvo thought that similar processes were possible for the neutral particles of the lepton-sector and came up with a theory.

---

6 Some of the cosmic muons reach sea-level before decaying to an electron. These energetic cosmic muons can penetrate thick layers of dense materials and therefore they often give a large contribution to the background of particle physics experiments.
of neutrino-antineutrino oscillations. It was only later, after the discovery of the second type of neutrino $\nu_\mu$, that he first applied his ideas to describe oscillations between different neutrino flavours [15].

We know now that neutrinos exist in three different flavours. In the framework of the weak interaction they can thus be treated as three different flavour eigenstates $|\nu_e\rangle$, $|\nu_\mu\rangle$ and $|\nu_\tau\rangle$. The propagation of neutrinos, however, is described in the mass basis with eigenstates $|\nu_1\rangle$, $|\nu_2\rangle$ and $|\nu_3\rangle$, corresponding to three different masses $m_1$, $m_2$ and $m_3$ respectively. The transformation from one basis to another is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & -s_{12} & 0 \\
s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
e^{i\phi_1} & 0 & 0 \\
e^{i\phi_2} & 0 & 0
\end{pmatrix},$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ ($i, j = 1, 2, 3$). The first three matrices correspond to the three rotations. The fourth one includes two phases $\phi_1$ and $\phi_2$, which account for the possibility of neutrino and antineutrino to be two states of the same particle. If this is the case, neutrinos are so-called Majorana particles. A third phase factor $\delta$ in

**Figure 1.3:** Left: The Super-Kamiokande set-up. [13] Right: Measurements of the muon neutrino distribution as a function of the zenith angle in the Super-Kamiokande experiment. [14]
the second matrix, accounts for $CP$ violation in the lepton-sector, which has not been observed in experiments so far.

\[ |\nu_1\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle. \] (1.9)

When this electron neutrino propagates over a certain distance, its mass eigenstates will evolve depending on direction $x$ and time $t$ as

\[ |\nu_i(x,t)\rangle = e^{i(p_x x - E t)} |\nu_i(0)\rangle \]
\[ = e^{i(E x - \frac{m_i^2}{2} x - E t)} |\nu_i(0)\rangle \] (1.10)
with $p_x$ the momentum along the direction of travel and $E$ the energy of the neutrino.\footnote{Using the energy relation and the fact that the neutrino masses are very small, one can write the momentum as $p_x \approx E - \frac{m_i^2}{2E}$.}

When it has travelled a distance $L$, the neutrino will be a superposition

$$|\nu(L,t)\rangle = \cos \theta |\nu_1(L,t)\rangle + \sin \theta |\nu_2(L,t)\rangle = e^{i(EL-Et)} \left( \cos \theta e^{-i\frac{m_1^2 L}{2E}} |\nu_1(0)\rangle + \sin \theta e^{-i\frac{m_2^2 L}{2E}} |\nu_2(0)\rangle \right). \quad (1.12)$$

Writing the mass eigenstates in terms of the flavour eigenstates, this becomes

$$|\nu(L,t)\rangle = e^{i(EL-Et)} \left( \cos \theta e^{-i\frac{m_1^2 L}{2E}} |\nu_e\rangle - \sin \theta |\nu_\mu\rangle \right) + \sin \theta e^{-i\frac{m_2^2 L}{2E}} \left( \sin \theta |\nu_e\rangle + \cos \theta |\nu_\mu\rangle \right). \quad (1.13)$$

The neutrino has thus become a superposition of two flavour states, with coefficients

$$c_e = \cos^2 \theta e^{-i\frac{m_1^2 L}{2E}} + \sin^2 \theta e^{-i\frac{m_2^2 L}{2E}} \quad (1.14)$$

and

$$c_\mu = \sin \theta \cos \theta (e^{-i\frac{m_2^2 L}{2E}} - e^{-i\frac{m_1^2 L}{2E}}). \quad (1.15)$$

The probability that an electron neutrino oscillated into a muon neutrino after traveling a distance $L$ is found from

$$P_{\nu_e \rightarrow \nu_\mu} = |\langle \nu_\mu |\nu(L,t)\rangle|^2 = |c_\mu|^2. \quad (1.16)$$

Writing $m_1^2 - m_2^2$ as $\Delta m^2$, one has

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right). \quad (1.17)$$

Because of some lucky circumstances, this simplified model of two flavour mixing can be applied to both solar ($\nu_e \leftrightarrow \nu_\mu$) and atmospheric ($\nu_\mu \leftrightarrow \nu_\tau$) neutrino oscillations. The main reasons for this are respectively the smallness of the mixing angle $\theta_{13}$ and the tiny mass difference $\Delta m_{12}^2$. The best fit values of the different mixing angles and squared mass differences, as they are known today, are given in table 1.3.

Since the oscillation experiments can only measure the disappearance or survival probability of a specific neutrino flavour (eq. 1.17), they are not sensitive to the sign of the mass differences. Therefore it is still unsolved which neutrino is the lightest and which is the most heavy one. There are two possibilities for this mass hierarchy; a normal one, with $m_{1,2} < m_3$, and an inverted one, with $m_3 < m_{1,2}$. Figure 1.5 shows the two configurations.
Table 1.3: Best fit values for the neutrino oscillation parameters in a three-neutrino mixing scheme. The values are obtained through a data analysis of a combination of different experimental results. [17]

| Mass differences | $|\Delta m^2_{12}|$ | $(7.53 \pm 0.18) \times 10^{-5} \text{eV}^2$  
$|\Delta m^2_{23}|$ | $(2.52 \pm 0.07) \times 10^{-3} \text{eV}^2$ (NMH)  
$|\Delta m^2_{13}|$ | $(2.44 \pm 0.06) \times 10^{-3} \text{eV}^2$ (IMH)  
| | $\approx |\Delta m^2_{23}|$ |
| Mixing angles | $\sin^2(2\theta_{12})$ | $0.846 \pm 0.021$  
$\sin^2(2\theta_{23})$ | $0.999^{+0.001}_{-0.018}$ (NMH)  
$\sin^2(2\theta_{13})$ | $1.000^{+0.000}_{-0.017}$ (IMH) |

NMH = normal mass hierarchy, IMH = inverted mass hierarchy.

Figure 1.5: Mass hierarchy in the three-flavour neutrino model: normal (left) or inverted (right). The mass difference $\delta m^2$ in the figure is the smaller difference, referred to as $\Delta m^2_{12}$ in the text. The $\Delta m^2$ corresponds with $\Delta m^2_{23}$ from the text. The figure also shows the relative contribution of the three flavour ($\nu_e$, $\nu_\mu$, $\nu_\tau$) states for each mass state. [13]

1.4 Neutrino Anomalies

At the moment, the framework of three-neutrino flavour oscillations is a nicely developed and well accepted theory. Observations within various types of experiments - from natural sources to man-made accelerator experiments - can be explained by this model. There are, however, indications from some oscillation experiments that this framework is not yet complete. These experiments and their corresponding anomalies can be grouped in three different types and are discussed in the following sections. The last section
includes a discussion on the sterile neutrino as a possible explanation for the three anomalies.

1.4.1 Accelerator Experiment Anomaly

The first results that did not fit in the three-flavour oscillation model came from the LSND experiment [18]. It was designed to measure the oscillation of $\bar{\nu}_\mu$ into $\bar{\nu}_e$ over a short baseline of about 30 meters. The muon antineutrinos originated from the decay chain of negative pions (see equations 1.7), which were produced at an accelerator facility. The electron antineutrinos were detected from inverse beta decay. The search resulted in a $3\sigma$ excess of $\bar{\nu}_e$ signals over the calculated background. This led to an oscillation fit with a squared mass difference $\Delta m^2$ between 0.05 and 100 eV$^2$, which was far larger than the values obtained from earlier solar and atmospheric neutrino experiments (cf. table 1.3).

The LSND results stayed unconfirmed for some years and were even contradicted by the KARMEN experiment, which conducted a similar search [19]. Since there was a difference in the baseline of the two experiments (30 m compared to 17 m), the KARMEN experiment could not fully exclude the oscillation probability, but it did significantly reduce the upper bound of possible $\Delta m^2$ values to 1 eV$^2$.

In 2007 the MiniBooNE experiment, that was specifically designed to investigate the LSND anomaly (it used the same $L/E$ ratio), published its results of a $\nu_\mu \rightarrow \nu_e$ oscillation search [20]. It found no evidence for these short baseline neutrino oscillations in the energy region above 475 MeV. The data for the region containing lower neutrino energies did show an unexplained excess of electron-like events. Two years later, the MiniBooNE Collaboration conducted a new search with antineutrinos to match the KARMEN and LSND conditions even better. This time, the MiniBooNE experiment unexpectedly did find a similar excess in the LSND region, pointing to the direction in favor of new oscillations [21].

1.4.2 Gallium Anomaly

Another anomaly in neutrino physics was found in the source calibration measurements of the SAGE and GALLEX detectors. Both experiments used the reaction

$$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- \quad (1.18)$$
to detect solar neutrinos. For the calibrations a radioactive $^{37}$Ar or $^{51}$Cr source was placed inside the detecting volume. The measured rate of the neutrino-capture in Gallium appeared to be much lower than predicted. Figure 1.6 shows the ratios of the measured versus predicted rate, calculated from four different experiments. Their combination results in a ratio of $0.87 \pm 0.05$, which is more than 2 standard deviations from unity.

This unexpected deficit of electron neutrino captures in the Gallium detectors is called the Gallium anomaly. It is another indication of some problems in the understanding of neutrinos and their oscillation properties.

### 1.4.3 Reactor Antineutrino Anomaly

The third kind of neutrino anomalies is found in nuclear reactor experiments. In these experiments, the $\bar{\nu}_e$’s coming from the reactor are detected at a fixed distance $L$ and the spectrum is compared with the expected spectrum from the three-flavour oscillation model. The ratio $R$ of detected and predicted rate of $\bar{\nu}_e$ at short baseline has been measured by various experiments (ILL, Bugey, ROVNO, Goesgen, ...) operating at reactor-detector distances between 10 to 100 meters. Until a few years ago, the combined data resulted in a value $R = 0.980 \pm 0.024$, which was still consistent with unity.

More recently, the spectra of reactor antineutrinos were reevaluated for different types of reactor fuel. These updated values result in an increase of the predicted mean reactor flux by about 3%. Although this is only a small increase, it brings the ratio $R$ of detected and predicted rate of reactor antineutrinos down to $0.927 \pm 0.023$; a deviation from unity at $3\sigma$-level (cf. figure 1.7). This deficit is known as the reactor antineutrino anomaly.

There exists a range of possible explanations for this anomaly. First of all the physics that take place inside the nuclear reactor might not be fully understood. A particular
Figure 1.7: The weighted average of 19 measurements of the ratio of measured to expected rate of antineutrinos. The measurements were conducted by different reactor experiments, operating at distances between 10 and 100 meters from the reactor core. The combined results lead to a deviation from unity at 98.6% C.L., known as the short baseline reactor antineutrino anomaly. [23]

difficulty in this research area is the reactor flux calculation. Different methods exist and they sometimes contradict each other. Figure 1.8 shows two calculated spectra for each of the two methods; the $\beta$-conversion method and the summation method. The results of the calculations differ by about 10 percent over the full spectral range.

Another reason for the anomaly might be a correlated effect in the measurements of the different experiments. This, however, seems unlikely, since they use different detection methods and they operate at different reactor plants, each with their own specific conditions. A third explanation is that the anomaly is evidence for new physics in the neutrino world. Here, again the current three-flavour picture of neutrino oscillations is questioned and the suggestion is raised that additional oscillations, involving a new type of neutrino, exist.

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The $\beta$-conversion method models the $\bar{\nu}_e$-spectrum by using the known correlation between the $\beta^-$ spectrum, which can measured with high precision, and the $\bar{\nu}_e$ spectrum. The summation method is based on existing nuclear data for various isotopes. It sums up the antineutrino spectra of all beta decays in the reactors fission and decay chains, taking into account the different decay rates and branching fractions for all daughter isotopes.
1.4.4 Sterile neutrino: the solution?

The three neutrino anomalies, discovered in three various fields of neutrino oscillation research, might all have one origin. The LSND and MiniBooNE experiments could be explained by new neutrino oscillations with a $\Delta m^2$ of a few eV. The assumption of such oscillations can also deliver a possible explanation for the Gallium anomaly. In this case, electron neutrinos could transform into a new type of neutrino over small distances. Additionally, the reactor experiments give a third indication that a fourth neutrino, inducing oscillations over short distances, might exist.

This hypothetical fourth neutrino would have to be a sterile particle. This is indicated by the LEP-results, as shown in figure 1.2, which prohibit the existence of an additional neutrino that couples to the Z boson. A new kind of neutrino therefore should not interact weakly, in contrast with the three active neutrinos that are currently known. As a result, it is given the name sterile neutrino.

The effects of a sterile neutrino oscillation can be illustrated, using the case of the reactor antineutrino anomaly as an example. This anomaly can not be explained by $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ or $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$ oscillations, since these are only significant at larger distances. To fit the current data, the oscillation must involve a sterile neutrino with a mass that is significantly larger than the active neutrino masses. Otherwise the oscillation would not manifest itself to such an extent at these short distances (see equation 1.17).
Figure 1.9 shows a possible sterile neutrino solution, fitted to the combined results of all short baseline reactor neutrino experiments (blue curve). The fit uses a 3+1-neutrino model of 3 active neutrinos and 1 sterile neutrino. The new oscillation parameters resulting from the fit are $|\Delta m^2_{\text{new}}| > 1.5\:\text{eV}^2$ and $\sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08$, both at 95% C.L.. A 3-neutrino solution fitting the data is also shown (red curve).

![Figure 1.9](image)

**Figure 1.9:** The black dots represent data from different reactor experiments. The red curve represents a fit to the data within the 3-neutrino hypothesis. The blue curve represents a fit using a 3+1-neutrino model, introducing 1 sterile neutrino. [25]

It can be seen that the largest difference between the two hypotheses occurs at very short distances, below 10 meters. Therefore, reactor experiments operating at these short reactor-detector distances, could provide information to prove or reject the existence of the sterile neutrino. This verification is becoming extremely important, given the persistence of the neutrino anomalies and their growing evidence in favor of new physics.

The SoLid experiment is one of the new projects, specifically designed to examine the reactor antineutrino anomaly at very short baselines. Its purpose is to differentiate between the different hypotheses that currently exist. Thus, it is one of the experiments that might give extra evidence in favor of the sterile neutrino. If not, the experiment will be able to give better limits on the existence of this hypothetical particle.
Chapter 2

SoLid Experiment

SoLid is short for “Search for oscillation with a $^6$Li detector”. The experiment is designed for the detection of reactor antineutrinos and will operate at a very short baseline. The goal is to evaluate the 3+1 neutrino hypothesis and thus prove or reject the existence of sterile neutrinos. The experimental set-up is located at the BR2 nuclear reactor of the research center SCK\-CEN in Mol, Belgium. The project was initiated at Oxford University and has now grown to a collaboration which also involves researchers from other British institutions, French research centers and three Belgian universities (UA, VUB and UGent).

2.1 Location

As shown in figure 1.9, the best differentiation between the 3- and 3+1-neutrino hypotheses should manifest itself at oscillation distances below 10 m. By measuring the antineutrino energy spectrum at different distances, a very short baseline reactor experiment should thus be able to resolve the oscillation pattern.

Therefore, the BR2 research reactor is the ideal operation site for the SoLid experiment. This is due to the fact that the reactor’s core can serve as a very intense and almost point-like neutrino source for the experiment and is thus very well suited to gain a high resolution on oscillation patterns.

The first advantage of the BR2 reactor is its very compact core of about 1 cubic meter, which allows the SoLid detector to be placed as close as 5.5 m from the reactor core. A sketch of the detector positioning in the reactor hall is given in figure 2.1. The reactor power can be tuned between 45 and 100 MW, according to the requirements of ongoing
irradiations or physics experiments [26]. This power range will allow an interaction rate of about 400 $\bar{\nu}_e$ per day for the full SoLid detector.

Another advantage of the BR2 reactor site are the very good shielding conditions. Because there are currently no other experiments conducted at the same floor of the reactor building, all other experiment gates in the hall are closed. This reduces the background significantly.

Figure 2.1: Sketch of the position of the SoLid experiment at the BR2 reactor site of the SCK•CEN in Mol. [27]

2.2 Detector configuration

The SoLid experiment uses an innovative composite scintillator technology to detect and differentiate between the neutron and positron resulting from an antineutrino interaction.\(^1\) It will employ a highly segmented detector of stacked scintillator cubes providing good localization of interactions. This makes the experiment more robust to backgrounds, which is of great importance when operating in the close proximity of a nuclear reactor where background rates are very high. The experiment will use several detector modules to enable data taking at different distances between 6 and 10 meters from the reactor core.

The detector modules are built up out of several aluminum frames, each containing 256 cubes of 5 cm by 5 cm by 5 cm (figure 2.2). The cubes are made of PVT (poly vinyl

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\(^1\) This scintillator technology is newly developed within the research of the MARS project conducted by people from Imperial College London and Oxford University [28]. The SoLid experiment started as a spin-off of this MARS project.
toluene) scintillator. When charged particles traverse the scintillator, they ionize this medium and thereby generate excited atomic states. The subsequent decay towards the ground state is accompanied by the emission of photons, which are used as scintillation light signal. The more energetic the particles are, the more scintillation photons they will produce.

For the detection of neutrons, a sensitive layer with a mixture of lithium fluoride (LiF) and silver doped zinc sulphide scintillator (ZnS(Ag)) is used. The lithium fluoride is enriched with $^6$Li, which enlarges the neutron cross section. These neutron sensitive layers are also 5 cm by 5 cm squares and are placed on one surface of each cube.

The scintillation photons from both the PVT cubes and the lithium sheets are collected and transported by wavelength shifting fibers with a cross section of 3 mm by 3mm. The fibers are placed inside grooves that are running in two adjacent edges of a cube. In such a way each cube is crossed by a perpendicular pair of fibers. This leads to very good position information for an event, since two simultaneous light signals coming from two perpendicular fibers can trace back to exactly one cube where the interaction took place. Each assembly of a PVT cube plus neutron sensitive layer is wrapped in a layer of synthetic Tyvek paper, to optically isolate a cube from its neighbouring cubes. In this way, light signals produced in one cube stay confined and are collected by one pair of fibers only, which preserves the good spatial resolution of the detector. A bare PVT cube is shown in the left picture of figure 2.3: a wrapped cube, into which one wavelength shifting fiber has been inserted is shown on the right.

Each wavelength shifting fiber is coupled to a Multi-Pixel Photon Counter (MPPC) on one of its ends. One MPPC consists out of thousands of pixels, that each detect

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pvt-cube-stack.png}
\caption{The PVT cubes are stacked in one layer inside an aluminum frame. A submodule of the SoLid detector exists of several of these frames, firmly attached to each other. [27]}
\end{figure}
photons using the principle of charge avalanche in Geiger mode. The total current coming from the MPPC is the sum of the currents from its individual pixels and is therefore proportional to the number of pixels which detected photons and subsequently triggered avalanches. The scintillation light produced in the detector and transported to the MMPCs is thus measured in units of pixel avalanches (PA). The photon counters are coupled to electronics boards and fast digitizers with coaxial cables. These electronic components take care of the read out, processing and storage of the data.

In addition to the composite scintillator cubes the detector modules also have a muon veto system. This system is constructed from plastic scintillator panels, each coupled to a single photomultiplier tube (PMT). The panels can be placed on the left, right, underneath and on top of the detector. These extra detector panels are used to have an additional discrimination tool for cosmic muon background, which is not easily filtered out by use of shielding materials. The PMT signals of the muon veto system are also fed to the read out electronics and are stored together with the other experimental data.

To reduce the backgrounds for the experiment, some layers of shielding are mounted on the detector modules. These layers are thick slabs of HDPE (high density poly ethylene), which prevent photons and environmental neutrons from entering the detector.

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2Photons of high energy create charge carriers when they hit a silicon pixel. A high enough electric potential is maintained (Geiger mode) so that the electrons produce an avalanche in which the number of electrons is multiplied [30]. For MMPCs this multiplication factor or gain is around $10^6$. The typical photon detection efficiency (PDE) is roughly 35%.

3A photo multiplier tube is a photon detection device, like an MPPC. Here the photons are converted to electrons by a photocathode. The electrons are multiplied by a dynode system [30].
2.3 Detection principle

When a reactor antineutrino hits the detector, it will interact with a proton of the detector material. The process of the interaction is an inverse beta decay (IBD):

\[ \bar{\nu}_e + p \rightarrow n + e^+. \]  \hspace{1cm} (2.1)

Figure 2.4 shows this reaction, caused by an antineutrino hitting a PVT cube of the detector. The resulting positron, which carries most of the neutrinos momentum, immediately causes scintillation light in the PVT.\(^4\)

![Figure 2.4: The IBD detection principle for the SoLid experiment. \([31]\)](image)

The resulting neutron thermalizes while elastically scattering through the material, until it is captured by the \(^6\)Li in the neutron sensitive sheets. This induces the reaction

\[ n + ^6\text{Li} \rightarrow ^3\text{H} + ^4\text{He} + 4.78\text{MeV}. \] \hspace{1cm} (2.2)

The triton and alpha particle are energetic enough to cause excitation of the electrons in the ZnS crystal. De-excitation of these states then results in a second scintillation signal. Due to the time taken for the neutron to scatter before capture, the second scintillation signal is delayed with respect to the signal from the positron. In addition, because of the finite lifetime of the ZnS excited states, which is significantly larger than the decay time of the PVT scintillator, the resulting waveforms of positron and neutron signals will have a different shape. Comparing the waveforms can thus help in discriminating

\(^4\)The positron later annihilates with an electron of the detector material, creating two 511 keV gamma rays that may also be detected.
positrons from neutrons. In general, the neutrons do not travel a large distance in the PVT cubes before they are captured by the $^6$Li and so the neutron signal is usually seen in the same cube as the positron signal or in one of the neighbouring cubes.\textsuperscript{5}

![Figure 2.5: The expected signals from an IBD event. The different lengths for the tails can be used to identify and separate positrons and neutrons. The time difference between the two pulses is the main feature of an IBD event. [31]](image)

In summary, the signature for an IBD event consists of a PVT scintillation signal consistent with a positron, followed a short time later by a neutron signal in a nearby cube. Figure 2.5 shows the expected detector signal for such an IBD interaction.

In addition to IBD events the detector is also sensitive to a number of background sources. Actually, the main challenge of oscillation measurements is to control the high level of background that is present close to nuclear reactor cores.

A large number of gamma rays is continuously emitted by the reactor. When these gamma rays Compton scatter with electrons in the scintillator cubes, their direction is randomized and electrons get decoupled from their atoms. The Compton scatter will thus give a very similar signature as a positron.

Although most of them are stopped by detector shielding, some environmental neutrons are also detected. The background signature which is undoubtedly the most arduous to reduce is a random coincidence of a gamma ray (similar to a positron signal) with an environmental neutron. Due to the high rate of gamma rays from the reactor, this coincidence occurs rather frequently. It is therefore the most dominant form of background for the experiment.

\textsuperscript{5}Simulations have shown that neutrons maximally travel about 15cm from the antineutrino interaction point, which corresponds with 3 cubes, before they are captured in a lithium screen.
Cosmic ray muons, since they are charged and energetic sparticles, also cause scintillation signals in the PVT cubes when they pass through the detector. The background caused by cosmic muons is the subject of this thesis and will thus be discussed in more detail in following chapters.

2.4 NEMENIX

The NEMENIX detector is an 8 kg prototype of the SoLid reactor antineutrino detector. It was built to test and demonstrate the new detection technology and to take some first data at the BR2 reactor site. This data has allowed the collaboration to gain experience with the detector’s operation principles and to measure the background conditions at the experimental site. It also gave the opportunity to develop methods to reconstruct events, which can eventually be used for the analysis of the data obtained by the larger scale modules.

NEMENIX exists out of 64 PVT cubes, forming a detecting volume of approximately 20 cm by 20 cm by 20 cm. The cubes are arranged as four horizontal layers, each with a 4 by 4 arrangement of cubes. The neutron sensitive layers are oriented parallel to the plane of the layer. There are 8 wavelength shifting fibers per horizontal plane in NEMENIX; 4 fibers are placed parallel in the x-direction, 4 others are oriented in the y-direction. The ends of the fibers are connected to MPPCs, which are in turn connected to the read out electronics with coaxial cables. Each layer of NEMENIX is handled with a different electronics board, numbered 0, 1, 2 and 3 from bottom to top. The cables for each of the eight fibers of a plane are connected with different channels on its corresponding board; the x-channels have numbers 0, 1, 2 and 3, the y-fibers correspond to channels 4, 5, 6 and 7.

NEMENIX is surrounded by four muon veto panels; two smaller ones, of 35 cm by 35 cm, on the left and right sides and two large ones, of 70 cm by 70 cm, on the top and bottom. Each panel is read out with a PMT, whose signals are processed with electronics board 4. This board thus contains 4 channels; left, right, lower and upper muon veto respectively correspond to channels 0, 1, 2 and 3.

The detector, along with its two small muon veto panels, is enclosed in a neutron shield made of HDPE. The two large muon veto panels, above and below the detector, are deployed outside the HDPE shielding.

The channel mapping and orientation of the muon veto panels and shielding are shown in figure 2.6.
The NEMENIX detector, in the configuration detailed above, started taking data at BR2 in July 2014. The reactor run of July-August 2014 consisted of approximately 20 days running at 63 or 60 MW. The run ended on the 5th of August.

After the run, reactor-off data was taken, which was used to determine backgrounds and to compare them with reactor-on data. The data used for the muon background analysis within this thesis exists out of several data-files, each containing about half an hour of data. These include one reactor run day of the 28th of July and reactor-off data from the 14th to the 28th of August.

In December 2014, the first submodule of the large scale SoLid detector was set up at the BR2 site. It took data during the reactor run of February 2015. A second submodule is planned to be ready for data-taking by the end of 2016.

### 2.5 Targets of the SoLid experiment

Evidence for the existence of the sterile neutrino would represent one of the most extraordinary discoveries in modern particle physics. It would open a part of nature that is really beyond the Standard Model. The existence of a sterile neutrino would have far reaching consequences, even outside the domain of particle physics [33].

An improved upper limit on the existence of a light sterile neutrino could, on the other hand, weaken or even fully reject the hypothesis of new oscillations as an explanation for the neutrino anomalies discussed in chapter 1.
Independent of the outcome, a new very short baseline reactor experiment will be of great help for the improvement of reactor antineutrino flux calculations, which will benefit future experiments using reactors as antineutrino sources.

The state-of-the-art detection technology of the SoLid experiment can provide a very accurate measurement in the region where the sterile neutrino is expected to be found (cf. figure 2.7). The detector’s high signal to background ratio plays an important role in the attempt to solve the current anomalies. The detector efficiency and reactor power should be sufficient to have a robust measurement of the very short baseline oscillation region within 2 years of running with the complete large scale SoLid detector.

![Figure 2.7: The SoLid experiment will be able to investigate not only the rate of antineutrinos, but also the shape of their spectrum. Adding the shape information will give the experiment a much better rejection capability, directly targeting the RAA (reactor antineutrino anomaly) region. [29]](image)
Chapter 3

NEMENIX Data Analysis

Prior to the discussion on the investigation of the various forms of muon background of chapter 4, this chapter will deal with the general concepts of the data analysis for the NEMENIX prototype. An overview of these concepts and their mutual links is given in section 3.1. The assumptions and parameters used for the reduction of the data to a smaller subset that is relevant for a muon study, are motivated in section 3.2. The last two sections, 3.3 and 3.4, focus on the consecutive steps of the data reconstruction process, which eventually lead to a collection of more physics related objects.

3.1 Framework Structure

For every run of the NEMENIX detector, the read out electronics produce large sets of data files. These files can be read and processed with the use of custom made codes, each programmed to perform a specific set of tasks or analyses.

In an earlier stage of this thesis, the data analysis steps were added to a C++ code written by Dr. Petra Van Mulders of the VUB. Over the past few months, however, the first steps have been taken to build up a common analysis framework for the SoLid Collaboration, up to now called the Ghent NEMENIX Framework. The principal concepts for this framework were developed by Dr. Mathieu Labare from the UGent. In order to contribute to its development, the earlier produced analysis steps serving the investigation of this thesis, were transformed to suit within the novel framework structure. The most recent parts of the analysis were directly developed and implemented in this new code.

An overview of the objects and hierarchy in the Ghent NEMENIX Framework, with a focus on the parts involved in the analysis of the muon background for this thesis, is given
in figure 3.1. This chapter will be dedicated to the first five levels of the diagram, which are the steps involved in the filtering and selection of data and the reconstruction of signals and events. The selection of specific types of muon-like events and their physical interpretation, shown in the last level of the diagram, are the topics of chapter 4.

### 3.2 Peaks: Definition, Investigation and Selection

The electronics coupled to the NEMENIX detector produce waveforms as output, showing a varying pulse height as a function of sampled time. The expression of the timing of the electronics signals in time samples is a consequence of the digital read out of the detector. The settings of the NEMENIX system are such that 1 sample corresponds to 10 nano seconds.
The waveforms form the raw experimental data of the experiment and are stored in ROOT files\(^1\), which each contain approximately 30 minutes of data taking.

To reduce the output for more optimal storage, an identification of the peaks within each waveform is performed for all data files. A peak is defined as a section of the waveform that starts three time samples before the waveform exceeds a high threshold and ends three samples after it falls below a lower threshold. For each peak, the amplitude is defined as the maximum value in the waveform segment. The integral of the segment, often referred to as integrated or total charge, is also calculated by integrating the peak over its pulse width in time.

Since the main goal for the experiment is to select and evaluate IBD events, peaks produced by neutron interactions are important. Therefore, a selection of neutron like peaks is also performed, in parallel with the reduction of the data. This selection is based on specific conditions on both the integral and amplitude of the peak.\(^2\) It should also be noted that only those peaks that are within a time window of 0.5 s of a neutron peak are stored. This provides another large part of the reduction of the data.

The identification of the (neutron) peaks and their properties was the work of Nick Ryder from Oxford University. The results of this process were again stored in ROOT files, which are significantly reduced in size compared to the raw data set. These reduced data files are the ones that are used as input for the data analysis, performed in the course of the investigation for this thesis.

### 3.2.1 NEMENIX and Muon Veto peaks

There are two types of peaks in the NEMENIX data. One type originates from particle interactions in the PVT cubes or lithium sheets, and is referred to in this text as NEMENIX peaks. These correspond to the light pulses that are collected and transported by the wavelength shifting fibers and that are read out by MPPCs. They are processed with the electronics boards 0, 1, 2 and 3, as mentioned in chapter 2. The properties of these NEMENIX peaks, such as their amplitude and integral, are expressed in MPPC units of pixel avalanches (PA).

The second type of peaks is selected from the waveforms produced by the muon veto panel system and are called muon veto peaks. Since this system is coupled to PMTs for the read out, the light pulse conversion and amplification methods differ compared to those of the NEMENIX peaks, that are read out by MPPCs. The unit used to

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\(^1\)ROOT is a framework that was developed at CERN for the storage, processing and display of high-energy physics data [34].

\(^2\)A detailed description of the conditions for the neutron selection is beyond the scope of this work.
describe amplitude and integral of the muon veto peaks is not PA, but analogue-to-digital converter or ADC counts.

In figure 3.2, two histograms combining all the peaks in the data set, display the correlation between the peak amplitude and integral. The information contained in this type of correlation plot will be referred to as the detector response in the following text. In the upper histogram the NEMENIX peaks are plotted, the lower plot shows the muon veto peaks.

![Figure 3.2: The NEMENIX detector response. Top: the peaks selected from the NEMENIX waveforms. Three separate zones are visible: EM particles, neutrons and cosmic muons. Bottom: the peaks selected from the muon veto system waveforms.](image)

By investigating the NEMENIX response, three different physical regions can be distinguished: the electromagnetic (EM) signals, such as electrons, positrons and photons, the neutrons and the cosmic muons. Both neutrons and EM particles produce peaks with
a relatively low amplitude, restricted to values below 50 to 60 PA. This is related to the moderate amount of energy that they deposit in the scintillator material. Because neutrons result in a longer pulse tail (see figure 2.5), the area under the pulse is larger compared to EM pulses. This results in higher values for the neutron integral.

The third component seen in this NEMENIX response plot, is the tail ending in a large blob at higher amplitudes and integrals. This region is dominated by the cosmic muons, which are energetic particles, crossing the detector. Because of their higher energies, they produce more intensive pulses, compared to the particles originating from an IBD event or the neutron background.

Since the focus of the research of this thesis is on cosmic muon background, the peaks responsible for this tail and its blob are the ones of interest. They are filtered out by using a high amplitude cut and only selecting those peaks with a higher amplitude (Peak Filter NEM). The amplitude threshold should be chosen on the edge between the electromagnetic and cosmic muon components, which seems to be located between 50 and 70 PA. Since the transition between the two components is fairly smooth, a precise determination of a threshold value is not straightforward. Therefore, a conservative but somewhat arbitrary value of 60 PA was chosen.

The lower plot in figure 3.2 contains the muon veto peaks, which are also of interest for a muon background investigation. The peaks in the veto panels show a more or less linear relation between their amplitude and integral. To be sure not to select noise, but to select signals induced by energetic muons, a furthermore arbitrary threshold of 200 ADC counts is set for these peaks (Peak Filter MV).

One can notice that a small collection of muon veto peaks at low amplitudes and relatively high integrals, in the top left corner of the histogram, deviates from the expected linearity. It was found that this effect is only seen in the two large horizontal panels of the veto system. Since these are the two panels that are mounted outside the HDPE shielding (cf. figure 2.6), it is possible that these low amplitude peaks are caused by other forms of background such as environmental neutrons or gamma rays. A further investigation of these peaks could provide more insight into the problem, but has so far not been performed.

### 3.2.2 Electronics effects

The detector response for the cosmic muons should extend linearly to higher amplitudes and higher integrals, as indicated by the bottom plot of figure 3.2. In the top plot of the figure, however, the amplitudes seem to be restricted to values below 110 PA, while...
the integrals show increasing values. This effect is due to saturation of the electronics. When enough scintillation light is emitted, the flood of photons produces the maximal pulse signal in the electronics. Therefore, highly energetic interactions all produce a maximal pulse height and the linear response breaks down for high amplitudes.

In case all MPPCs would have exactly the same response, the saturation would manifest itself at one PA-value. This would result in a vertical barrier in the response plot. In the case of figure 3.2, a blob with more rounded barriers shows up, pointing towards different saturation values for different channels. This indication was verified by plotting the peak amplitudes versus integrals for every separate channel of the NEMENIX detector. The responses of two of the thirty-two channels are shown as an example in figure 3.3.

![Figure 3.3](image)

Figure 3.3: The peak amplitudes versus integrals are shown for the peaks originating from two different channels; x 1 in board 3 (top), y 1 in board 1 (bottom). The saturation amplitude varies for the different channels.
The figure illustrates that the amplitude distributions of the two channels indeed end at different PA-values and proves that the channels’ saturation values differ. More importantly, this difference in the position of the saturation lines indicates that the channels’ MPPCs do not all have the same gain.

By studying this detector response per channel, another remarkable feature shows up. As is clearly visible in the top plot of figure 3.3, the high amplitude distribution is split up in two regions. The origin of this feature is most probably linked to the voltage settings for the MPPCs, varying over time.

This is seen, for example, when using an input of only 3 data files that are sequential in time, as in the top plot of figure 3.4. Here, there is only one saturation line seen. Adding a fourth consecutive file, and showing the response of the same channel as in the top plot of this figure, suddenly a second saturation region shows up.\(^3\)

### 3.3 Signal Reconstruction

As explained in section 2.2, the light pulses that originate in one of the cubes are transported by one specific combination of two perpendicular fibers. In this way, excellent position information can be achieved and the spatial resolution for the SoLid experiment is very high. On the other hand, this dual read-out of the cubes requires an extra step of reconstruction on the level of data analysis. This step is referred to as *Signal Finder* in the overview in figure 3.1 and is discussed in the following paragraph.

#### 3.3.1 Two peaks, one signal

To find *NEMENIX signals*, which represent an interaction in one of the 64 cubes, the NEMENIX peaks need to be matched.\(^4\) A possible match first of all requires one x-channel peak and one y-channel peak, both linked to the same board. This already corresponds to a pair of fibers that collected photons in one specific cube. A match of two peaks is then only stored as a signal if the peaks occurred within a limited time frame with respect to each other. The choice of an appropriate value for this time frame is motivated in subsection 3.3.2.

\(^3\)Also for the generation of figure 3.3, only a limited amount of 7 input files was used. This corresponds to about 3.5 hours of data taking. When using input data from several days, each channel shows a single saturation blob instead of multiple saturation lines. This indicates that the voltage settings continuously vary over time.

\(^4\)From this point on, the following discussions and plots only involve those NEMENIX peaks that have passed the *Peak Filter NEM* and the muon veto peaks that have passed the *Peak Filter MV*, unless otherwise specified.
The resulting signal inherits some properties of both of its contributing peaks:

- Signal amplitude; the sum of the two peak amplitudes,
- Signal integral; the sum of the two peak integrals,
- Signal time; the minimum of the two time-values.

Because the timing of the data is expressed in sample numbers, the time-stamp assigned to the peaks, and consequently also to the signals, is not highly precise. This finite timing resolution and other inevitable imperfections in the process of the detector read out, complicate the reconstruction of signals. One difficulty originates from the fact that
it is often possible that a peak gives valid matches with multiple other peaks. In this way, one peak can - from the reconstruction point of view - contribute to more than one signal, while this is physically impossible.

A *Multiple Signal Finder*-function was developed, keeping all possible signals that correspond to a valid match of two peaks. In parallel, the number of signals to which a peak contributes is tracked and stored as a parameter for each peak, called the *signal multiplicity*. Figure 3.5 shows a histogram of the signal multiplicity of the NEMENIX peaks.

![Figure 3.5: The signal multiplicity (i.e. the number of signals to which one peak contributes) for the NEMENIX peaks after signal reconstruction with the Multiple Signal Finder tool.](image)

Almost all the peaks in the muon selection are matched; only a very small number has multiplicity 0, meaning that they do not contribute to a signal. The majority of the NEMENIX peaks has multiplicity 1. These only give one valid match, which is the ideal case for clean signal reconstruction and good conservation of the position information. The maximal signal multiplicity is found to be 4. This is in accordance with what one would expect from the detector geometry; 1 x (y) fiber can maximally match with all 4 crossing y (x) fibers. Luckily, a signal multiplicity of 4 is seen for only a small minority of the peaks.

Overall, it can be concluded that the allowance of signal multiplicity does not create extreme ambiguities in the reconstruction process. Moreover, because of the limited timing resolution, allowing signal multiplicity for the peaks might, in some cases, even be necessary for a correct interpretation of the data.
Consider for example the case where an interaction occurs in which two adjacent cubes collect light. In the ideal case this would result in four peaks; one in each of the two individual x (y) fibers and two peaks which are extremely close in time on the common y (x) fiber. In reality, however, the timing is most probably not precise enough to separate these latter two peaks. As a consequence, the interaction in the adjacent cubes, will result in two peaks on the individual x (y) fibers an one fused peak on their common y (x) fiber. In this case, the interaction will only be reconstructed in accordance with the physical reality if signal multiplicity is allowed.

Therefore, the analysis is continued using the *Multiple Signal Finder* as the basic tool for the construction of signals. It should be kept in mind, however, that this method of signal reconstruction is only approximate and might sometimes be in conflict with the physical reality.

The peaks of the muon veto panels do not require a second step of matching, since each muon veto panel is read out by one channel and the panels are not designed to give precise position information for the interactions. The muon veto peaks are therefore also *muon veto signals*.

### 3.3.2 Peak time matching

To find a valid signal, a combination of two NEMENIX peaks should not only fulfill topological conditions (board, x and y), but it should also be a match in time. To allocate a certain value to the allowed time difference between two peaks forming a signal, the distribution of time differences between all possible pairs of peaks is investigated. In figure 3.6 four histograms are shown; only the time differences between peaks within the same board are of interest, since signals cannot be constructed by combining peaks of different layers (boards) of the detector.

Each of the four plots shows that a vast majority of the NEMENIX peaks - note the log-scale for the y-axis - lie within 2 or less samples from each other. Since this is already a very confined distribution, a strict timing coincidence condition will not drastically influence the selection of the peaks. The allowed time difference is set at the value of 4 samples. As a consequence most of the possible pairs of peaks are kept, but the pairs which result in a time difference in the tail of the distribution are left out.
3.4 Event Composition

Once all the possible signals for NEMENIX and the four muon veto panels are found, their mutual links can be investigated. In other words, a next reconstruction step can be performed, combining signals within a certain time frame to form a coherent event. These events can later be identified to correspond to a physical object or interaction, based on the number and topology of involved signals and their amplitudes and integrals.

3.4.1 Signal time matching

For a global reconstruction of any type of events, the only condition for valid combinations is on the time difference between the signals. Although it is very important in the case of reconstruction from peaks to signals, here the topology is not of primary concern. If specific types of events are of interest, the topology can, however, be an important restriction for the event selection. This subdivision of events per topology and other characteristics is part of the more profound discussion on the muon background analysis in chapter 4.
As was done for the peaks, the distribution of the time difference between all pairs of signals is investigated. Figure 3.7 shows the time differences between signals from all different boards.

![Figure 3.7: The time differences between the two signals in all possible pairs of NEMENIX and muon veto signals.](image)

Here, it has to be taken into account that signals from different boards are combined and each of the electronics boards can have a slightly different timing. Adding a board time correction, characteristic for each of the boards, removes the possible timing discrepancies between them. Furthermore, it is important to note that for this investigation also the muon veto signals are included.

Based on the distribution of the time differences in figure 3.7, the timing restriction for the combination of signals in an event is set as a maximal time difference of 13 samples. In this way, signal combinations with larger time differences, that occur relatively infrequent and most probably correspond to a mismatch, are rejected.

### 3.4.2 Event Viewer

To visualize an event, composed of multiple signals, an Event Viewer tool was developed. It produces a 3D image of the cubes and muon veto panels that show a signal within one event and thus allows one to interpret an event at sight.

Figure 3.8 contains a plot of the complete setup of the Event Viewer. It shows the stacked array of cubes and the surrounding muon veto panels. The arrow indicates the direction of the incoming reactor antineutrinos and is used as a reference for the channel numbering.
Figure 3.8: A simplified visualization of the detector setup, produced by the Event Viewer tool. The plot gives an indication on the numbering of the channels and boards with respect to the BR2 reactor position.

Apart from the global event topology, the viewer can also show one of the properties of the signals by using a color code. It can be chosen to either visualize the integral, the amplitude or the time of each signal in its corresponding cube. Figure 3.9 shows an example. The muon veto panels that are triggered are always shown without indication of the characteristics of their signal; i.e. they always have the same color.

One should keep in mind that this tool gives a rather qualitative image of the event. The relative dimensions and distances between the cubes and muon veto panels do not fully correspond with the exact set up of the NEMENIX detector.
Figure 3.9: An example of an event visualized by the Event Viewer tool. Four cubes show a high amplitude signal and two of the muon veto panels are triggered.
Chapter 4

Muon Background Evaluation

Cosmic ray muons cause scintillation signals in the PVT cubes when they pass through the NEMENIX detector. Because these muons are very energetic, they can penetrate thick layers of material and they are thus not easily stopped by the detector’s HDPE shielding. Therefore, cosmic muons give a significant contribution to the background of the SoLid experiment.

The muon background manifests itself in various forms. Muons that cross a large part of the detector form a long track of signals. Reconstruction of these muon tracks is useful to distinguish the background muon signals from positrons which are part of the sought-after IBD signal. Muons can also clip the detector, passing through only one or a few of the cubes on the edge of the detector. As a consequence, such clipping muons appear more similar to positrons. They should, however, also leave a signal in the muon veto system. Therefore, an investigation of the coincidences of muon veto signals can discriminate them from EM signals.

This chapter will deal with the identification of the different kinds of muon background. The first section, 4.1, incorporates a more general investigation of the NEMENIX signals for events with a coincidence between the two horizontal muon veto panels. Further on, the selection process of more specific events is treated in separate sections; starting with vertical muons in section 4.2 and continuing with clipping muons in section 4.3. Afterwards, in section 4.4, a comparison is made between the results from analyses using reactor-off data and using reactor-on data. The last section includes a small discussion on other possible types of muon background and how these can be investigated.
4.1 Muon like events

To get a first global image of the interactions of cosmic muons in NEMENIX and their resulting signatures in the data output, a rather conservative selection of events is appropriate. Therefore, it is most convenient to search for events which have a signal in the muon veto system, as well as in NEMENIX. This increases the likelihood of selecting only those events that were actually induced by a cosmic muon.

4.1.1 Selection of muon like events

Cosmic muons that reach sea-level generally follow a $\cos^2 \theta$ angular distribution, with $\theta$ the azimuthal angle [35]. Therefore, it is expected that significantly more muons enter the detector from above than from the sides. When plotting the number of signals for the four muon veto panels, as shown in figure 4.1, it is seen that channels 2 and 3, which correspond to the lower and upper muon veto panel, detect a lot more signals than channels 0 and 1. This is in accordance with what one would expect, since the two horizontal panels have a much larger horizontal area than the two vertical ones at the sides.

![Figure 4.1: The number of muon signals for every muon veto panel. Channels 0, 1, 2 and 3 correspond respectively to the left, right, bottom and top muon veto panel.](image)

Therefore, this first part of the muon background investigation focusses on events in which the horizontal muon veto panels, placed above and below the detector, were involved. For these events, it is studied what the NEMENIX response was in terms of the number of NEMENIX signals, their amplitudes, the topology and so on.

In the following discussion, two separate cases are considered:
1. events with a signal in upper and lower muon veto panel for which at least 1 cube in NEMENIX had a signal,

2. events with a signal in upper or lower muon veto panel for which at least 1 cube in NEMENIX had a signal. Here, the or is used as an exclusive condition; only one muon veto panel is triggered in that case.

Note that no further requirements were set on the signals in the left and right muon veto panels. They may or may not be involved in the selected events.

The first of the two cases will be referred to as the AND-case in the following paragraphs, the second one as the OR-case. The discussion on these events will start with a comparison of the contributions of the upper and lower muon veto panel for events that do and events that do not have a signal in NEMENIX.

4.1.2 Detection efficiencies

Table 4.1 shows a quantitative comparison of the fractions of events which involve the upper and lower muon veto panels, relative to the total number of events\(^1\) that contain a signal in one or in both of these panels. Three columns are present; the first one contains the numbers for a study that did not set any requirements on the presence or absence of NEMENIX signals, the second one presents an investigation that required the events to have at least one signal within the NEMENIX detector - resulting in the AND- and OR-case - and the third column shows the numbers for a selection of events that did not show any signal in NEMENIX.

The requirement of a signal in NEMENIX significantly changes the relative contributions of the upper, lower and combined muon veto events. It seems that in this case, slightly more coincidences appear between NEMENIX and the lower muon veto panel than between NEMENIX and the upper muon veto. One should note that this is in stark contrast with the overall tendency that the upper muon veto panel detects much more signals than the lower one. This effect is most probably a consequence of the fact that NEMENIX is closer to the lower muon veto panel than it is to the upper panel (cf. figure 2.6). The use of simulations, which allow one to play around with different distances in the detector set-up, should be able to confirm or reject this hypothesis. Within an earlier investigation of the performance of the muon veto system for the NEMENIX prototype, Céline Moortgat developed a simulation of the interaction of cosmic muons with the detector set up [32]. With this simulation, a similar effect of the geometry on the detection efficiencies was observed.

\(^1\)The total number of events is calculated as the sum of strictly up + strictly low + up and low.
Table 4.1: The relative fractions of events containing a signal in the upper or lower muon veto panel or in both. Three separate investigations are considered, depending on the conditions set on the events, regarding their NEMENIX signals. The bold values represent the OR-case and AND-case events as described in section 4.1.1.

<table>
<thead>
<tr>
<th>MV panels</th>
<th>all events</th>
<th>with NEMENIX</th>
<th>w/o NEMENIX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fraction [%]</td>
<td>fraction [%]</td>
<td>fraction [%]</td>
</tr>
<tr>
<td>Strictly up</td>
<td>59.144 (0.475)</td>
<td>27.583 (0.205)</td>
<td>82.823 (0.385)</td>
</tr>
<tr>
<td>Strictly low</td>
<td>20.464 (0.289)</td>
<td>29.023 (0.246)</td>
<td>14.042 (0.318)</td>
</tr>
<tr>
<td>Up and low</td>
<td>20.391 (0.229)</td>
<td>43.392 (0.252)</td>
<td>3.135 (0.082)</td>
</tr>
<tr>
<td>Total up</td>
<td>79.536 (0.289)</td>
<td>70.977 (0.246)</td>
<td>85.958 (0.318)</td>
</tr>
<tr>
<td>Total low</td>
<td>40.856 (0.475)</td>
<td>72.417 (0.205)</td>
<td>17.177 (0.385)</td>
</tr>
<tr>
<td>Rate [Hz]</td>
<td>5.537 (0.120)</td>
<td>2.373 (0.052)</td>
<td>3.163 (0.082)</td>
</tr>
</tbody>
</table>

Very striking is the variation of the fraction of coincidences for the up and low-case over the three columns. It shows that events with a muon candidate signal in NEMENIX often also show a coincidence in the upper and lower muon veto panels. Moreover, this case is strongly disfavored for events that do not contain a NEMENIX signal.

To have an idea of the frequency of occurrence of the events, the event rates are calculated for each of the three columns in table 4.1. The given values represent the rate for the total number of events for that column. The rate of specific cases, such as the AND-case and the OR-case can be found by multiplying their fraction of occurrence with the given rate.

Figure 4.2 shows the measured rate per day for the AND- and OR-case events. A calculation of the mean rate from these thirteen values gives a rate of $1.067 \pm 0.021$ Hz for the AND-case and $1.343 \pm 0.034$ Hz for the OR-case.

From figure 4.2, it is seen that the variation between the data points is significantly larger than the error flags that these rates are assigned. This indicates that either the errors are too small, either the physical rate is not constant over time. The following paragraph gives a discussion on the determination of the errors for event rates, showing that the error flags given in this figure are underestimated.

Another feature that shows up in this figure and is worth noting, is that the pattern of the rate evolution over the presented days is very similar for both the AND-case and the OR-case plot.\(^2\) This recurring pattern points towards an external effect on the detector’s

\(^2\)The similarity in the rate evolution over the days under investigation not only shows up between the plots shown here. It also appears in following rate-over-time plots for other types of muon background.
performance. Temperature fluctuations could be a possible origin of this phenomenon, however it hasn’t been possible to confirm this hypothesis so far.

4.1.2.1 Calculation of errors for rates

Since the event rate is equal to the number of events divided by the time over which events were collected, one should take into account two errors; one for the number of counts, $\delta(C)$, and one for the time interval, $\delta(t)$. The error on the event rate, $\delta(r)$, follows from the standard rules of error propagation:

$$\delta(r)^2 = \left(\frac{\delta(C)}{t}\right)^2 + \left(\frac{C\delta(t)}{t^2}\right)^2. \quad (4.1)$$

For the calculation of the error on the number of events $N$, Poisson statistics can be used. This gives a standard deviation of $\sqrt{N}$.

The determination of the error in the total measuring time is less straightforward. One could assume that the time is known with very high precision and assign no error to it. In principle this is not realistic, especially not for this investigation. Because the data files only include those events within the time window around a neutron signal (cf. section 3.2), the data input is not continuous over time. The total measuring time is thus determined as the sum of time intervals in which data was stored. Therefore, the possibility for uncertainties to sneak in is certainly not zero, as is the error in the value for the total measuring time.
However, since there is no known physics-related error, it is hard to decide on which error to choose for the time. As a consequence, only the error on the number of events was taken into account for the calculation of the error on the rates per day. From equation 4.1, with $\delta(t) = 0$ and $\delta(C) = \sqrt{N}$, one finds that

$$\delta(r) = \frac{\sqrt{N}}{t}. \quad (4.2)$$

Because this error is an underestimation, the values for the rate per day will be non-reproducible when calculating their average value. The error on the mean, for which the weight of the individual errors is accounted for, is thus calculated as the standard deviation $\sigma$ of the rates.

Keeping all these considerations in mind, one should not interpret the rates given here and in the following sections as utmost reliable. Rather, they can serve as a reference to compare the frequencies of the different kinds of events.

### 4.1.2.2 Calculation of errors for efficiencies and fractions

The calculation of the errors for the fractions or efficiencies that are presented above, is based on Bayesian statistics, following the ideas of T. Ullrich and Z. Xu [36]. The more common approaches, using Poisson or binomial errors, are not fully justified for the error calculation of efficiencies.

Assume a number of events $k$ that pass a selection, performed on a total number of events $N$. Using this data, the estimation of the efficiency $\hat{\epsilon}$ is $k/N$.

To perform a calculation of the error for this estimate with Poissonian statistics, the values $k$ and $N$ are treated as independent. Their errors are thus, respectively, $\sqrt{k}$ and $\sqrt{N}$. The standard method of error propagation then results in

$$\delta(\hat{\epsilon}) = \frac{k}{N} \sqrt{\frac{1}{k} + \frac{1}{N}}. \quad (4.3)$$

However, since $k$ and $N$ are highly correlated in these efficiency measurements, the use of Poisson statistics is certainly not valid.

The binomial error calculation seems more suitable for this problem. It is based on the probability $p$ for one event out of the total number of $N$ events to satisfy the selection criteria. In this case, the probability $p$ is the same as the true efficiency $\epsilon$. Using the standard formula for the binomial error and replacing $p$ by $\epsilon$, one finds

$$\delta(\epsilon) = \sqrt{\frac{\epsilon(1-\epsilon)}{n}}. \quad (4.4)$$
The problem with this approach lies in the fact that one can not know the real or true efficiency, but only has an estimate of the efficiency $\hat{\epsilon}$ from the data. This makes the binomial error calculation unreliable, especially in the limits of where $k$ is close to 0 or $N$.

A more intuitive solution for the error in $\hat{\epsilon}$ can be found with the use of Bayes’ Theorem. The calculation uses the probability density function $P(\epsilon; k, n)$, which gives the probability distribution of $\epsilon$ for given values of $N$ and $k$. The assumptions and analytical derivations for the calculation of the function and its mean, variance and error can be found in reference [36]. The resulting formula for the error in the estimated efficiency is

$$\delta(\hat{\epsilon}) = \sqrt{\frac{(k+1)(k+2)}{(N+2)(N+3)} - \frac{(k+1)^2}{(N+2)^2}}. \quad (4.5)$$

It is this formula that was used for the calculation of the errors on the coincidence fractions. The equation is also used for the efficiency error calculation in following sections; in tables 4.1, 4.2, 4.3 and 4.4.

### 4.1.3 Event properties

After the quantitative investigation of the event fractions and rates, this section will focus on the qualitative properties of the AND- and OR-case events. More specifically, the signatures of these events within the NEMENIX detector are studied. For each property under investigation, the two cases are compared, to see if a selection on specific muon veto coincidences influences the event’s characteristics within NEMENIX.

To have some global information on the events, the NEMENIX detector response is the first to be investigated. Figure 4.3 contains an amplitude-versus-integral plot for each of the two cases; the AND-case is shown in the upper histogram and the OR-case in the lower one.$^3$

As expected, the saturation blob shows up for each of the two cases. Note that the shape of the distribution differs from the one shown in figure 3.2, because here the NEMENIX signals are used as input and not NEMENIX peaks. This also explains the higher amplitude and integral values, seen in this distribution.

No striking qualitative differences are seen between the two responses. However, it can be noticed that the distribution has a much more intense peak - the fraction of entries

---

$^3$As seen in the previous section, the number of events contributing to the AND-case is smaller than the number of events that belongs to the OR-case. Therefore, the plots in figure 4.3 are scaled, i.e. divided by the number of events, to enable a qualitative comparison of the two. This was also done for the other histograms that are shown in this section.
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Figure 4.3: The NEMENIX detector response for the two cases: AND-case (top), OR-case (bottom).

is about a factor of 5 higher - for the AND-case, compared to the OR-case. A possible explanation for this effect is that, per event, more cubes with a signal might be involved for the AND-case, compared to OR-case events.

This is indeed seen in figure 4.4, which shows the number of NEMENIX signals per event for the selection of AND- and OR-case events.

The distribution for the AND-case contains a peak around 4 to 5 signals. This seems to be an indication for a large contribution of through going muons, which leave a full track in the NEMENIX detector, hitting 4 or more cubes. This hypothesis was strengthened by a study of the number of triggered cubes per layer of NEMENIX, which showed that most of the AND-case events had 1 cube hit per board.

The distribution of the OR-case events peaks at a significantly lower number of signals. Most of these events contribute to a signal in only one cube of the detector. This could
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Figure 4.4: Distribution of the number of cubes with a signal for the events that comply with the AND-case (top) and events that comply with the OR-case (bottom).

be the signature of clipping muons, which hit a cube on the edge of NEMENIX.

Figures 4.5 and 4.6 show the amplitude and integral distributions for the two cases, as a function of the number of cubes in the event. It should be taken into account that the histograms are filled once with the average amplitude and average integral for each event. This was done to be able to compare amplitudes (integrals) for events with a different number of signals. The average amplitude (integral) per cube in an event further has no physical meaning.

Looking at the plots for the amplitude as well as for the integral, the distributions clearly peak at 4 to 5 signals for the AND-case and at 1 signal for the OR-case, as was expected from figure 4.4. Comparing the distributions in amplitude and integral for the two cases, it is seen that they are broadened and partly extended towards lower values. The lower amplitude and integral values indicate a slightly lower amount of deposited energy per cube. This corresponds to what is expected, since clipping muons do not necessarily
cross a full cube, but might also cross only a small corner of it. Events of the AND-case, on the contrary, will mostly be due to muons with a larger track, for which most cubes are crossed over their full length.

For the OR-case events, also a relatively large number of events with 2 or 3 cubes at high amplitudes shows up. These could be muons which diagonally cross a few layers of NEMENIX. Another possible explanation is that part of these events include stopping muons, which lose enough energy to stop them before they reach the lowest layer(s) of NEMENIX.

Based on the results of this section, the following investigation will focus on two clearly separable cases; vertical muons, which give a signal in both horizontal muon veto panels and in a tower of 4 cubes in NEMENIX, and clipping muons, which hit either the upper or lower muon veto panel and light up one of the edge cubes of NEMENIX.
Figure 4.6: The distribution of the average integral per cube as a function of the number of cubes with a signal in the event for AND-case (top) and OR-case events (bottom).

4.2 Vertical muons

Because of their $\cos^2 \theta$ distribution, a lot of the muons that cross the full NEMENIX detector are expected to leave a more or less vertical track. For these events, there should be a signal in one cube for each of the four detector layers, together forming a vertical tower. With the dimensions of a cube being 5 cm by 5 cm by 5 cm, muon tracks with a maximal angle of $\theta \approx 14^\circ$ will show up as vertical muon events in NEMENIX.

4.2.1 Vertical muon event selection

The selection of a vertical muon event can be divided in three consecutive screening steps.
1. Topology. The event must have a signal in each of the four detector layers, furthermore these signals should be located in cubes that are at the same x-y position in every layer. It is also required that the upper and lower muon veto panels detected a signal.

2. Timing. The four NEMENIX signals should all have been detected within a limited time range. Moreover, also the muon veto signals should be in coincidence with these signals in NEMENIX.

3. Isolation. The cubes adjacent to the so-called tower of cubes are not allowed to have a signal within the same time interval. This is required to exclude events where, due to saturation or noise in the electronics, large clusters of cubes or sometimes almost all of the NEMENIX cubes seem to have a signal. Also tracks which are slightly off axis with the vertical and give a signal in some of the adjacent cubes of the tower are discarded with this approach.

The timing condition that is set on the signals of a vertical muon event is the standard one for events, allowing a maximal time difference of 13 samples, as discussed in section 3.4. However, the time difference of the NEMENIX signals which build up a vertical muon intrinsically have a narrower distribution, as seen in figure 4.7.

![Figure 4.7: Distribution of the time differences between the four signals in the NEMENIX cubes, building up a vertical muon tower.](image)

This shows that for a proper selection of vertical muon events, the two criteria of topology and isolation are sufficient, since they automatically select events that are also very coherent in time.
The isolation requirement for the vertical muons is kept very strict. As explained above, it is demanded that the cubes adjacent to the 4 cubes which build up the vertical tower do not show any signal within the event of the vertical muon. This involves not only the high amplitude NEMENIX signals, which are expected to correspond to a muon interaction, but also lower amplitude signals which might be induced by other particle interactions. Therefore, a second group of signals is identified, which combine two peaks which each have an amplitude of 20 PA\textsuperscript{4} or more. The adjacent cubes are thus screened on signals with an amplitude of 40 PA or higher. If one of them contains such a signal, the vertical muon candidate is rejected.

An example of the resulting vertical muon events, selected using the method described above, is given in figure 4.8.

\textbf{Figure 4.8:} An example of a vertical muon event, displayed with the Event Viewer tool. The integral of the charge deposited in each of the four cubes is represented with the color index.

\subsection{4.2.2 Vertical muon rate}

The rate of the vertical muon events, measured with the NEMENIX detector, can be determined by counting the number of vertical muon events and dividing by the total

\footnote{The value of 20 PA is chosen as a threshold to select all peaks which most probably correspond to a physical process, rather than to noise.}
measuring time. This straightforward approach results in a value of $0.0248 \pm 0.0013$ Hz. Figure 4.9 shows a plot of the rate of vertical muons over time.

![Figure 4.9: The vertical muon rate, calculated by dividing the number of vertical muon events with the measuring time.](image)

From cosmic ray studies, it is known that the integral intensity of muons at sea level is approximately $1 \text{ cm}^{-2} \text{ min}^{-1}$ for horizontal detectors [35]. To convert this rate to a value that is applicable to vertical muons in NEMENIX, one has to take into account the $\cos^2 \theta$ distribution of cosmic muons and the maximal allowed angle $\theta_{\text{max}}$ for vertical events. The fraction $F$ of vertical muon events can then be found as

$$F = \frac{\int_0^{\theta_{\text{max}}} \cos^2 \theta \, d\theta}{\int_0^{\pi/2} \cos^2 \theta \, d\theta}.$$  \hspace{1cm} (4.6)

Using $\theta_{\text{max}} \approx 14^\circ$, one finds that the fraction of vertical muons $F$ is about 30.56%.

Secondly one has to take into account that NEMENIX has a horizontal surface of about 20 cm by 20 cm. Combining these data, it is found that the rate or intensity of vertical muons, that NEMENIX should measure in the ideal case, is 2.04 Hz.

Compared to this ideal vertical muon rate, the rate detected by NEMENIX is about a factor of 80 lower. There exists a range of factors that affect the vertical muon counting rate for the NEMENIX set up. For example, the detector is located in the bunker of a nuclear reactor plant of which the concrete walls perform shielding of cosmic rays. Also
the intrinsic detection efficiency of both the muon veto system and the cube assembly of NEMENIX lower the number and thus the rate of detected muons.

To have an idea of the efficiency within different regions of the NEMENIX detector, the rate or number of vertical muons can be compared for each of the 16 possible positions. In figure 4.10 a plot of the distribution of vertical muons in the NEMENIX detector, viewed from the top, is shown.

![Figure 4.10: The distribution of vertical muons over the 16 different cube positions in NEMENIX.](image)

The regions on the front, left and right side show a higher intensity of vertical muons, compared to the positions in the middle. This can be due to the requirement of isolation of the tower, which is less strict for positions at the edge, since these have less adjacent cubes. The two corner positions on the front side detect even more vertical muons, compared to all others. This can again be explained by the fact that here, the isolation requirement has even less influence.

The difference in the number of detected vertical muons between the front side, facing the reactor, and the back side of NEMENIX can not be readily explained.

### 4.2.3 Coincidences with the muon veto system

The vertical muon candidates can also be used to give an estimate of the efficiency of a part of the muon veto system. This can be done by counting the proportion of the vertical muon towers in NEMENIX that also have a coincident signal in the upper and
lower muon panels. Table 4.2 gives an evaluation of the requirement of a coincidence between the vertical tower of cubes and the upper and lower muon veto panels.

**Table 4.2:** The fractions of coincidences of vertical towers of signals in NEMENIX with the upper and/or lower muon veto panels.

<table>
<thead>
<tr>
<th>MV panels</th>
<th>fraction of coincidences [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up and low</td>
<td>64.728 (1.910)</td>
</tr>
<tr>
<td>Total up</td>
<td>92.979 (0.644)</td>
</tr>
<tr>
<td>Total low</td>
<td>91.472 (0.901)</td>
</tr>
<tr>
<td>No up, no low</td>
<td>0.510 (0.258)</td>
</tr>
</tbody>
</table>

Table 4.2 illustrates that the muon veto efficiency is very high for coincidences with a single muon veto panel. Almost none of the vertical muon candidates are not detected by any of the two horizontal panels. For the vertical muons, however, one expects to have a coincidence with both the upper and the lower muon veto panel. For these *triple* coincidences, the fraction lowers to 64.728 $\pm$ 1.910%. This reduction can be partially attributed to the intrinsic efficiency of the muon veto detector panels.

Before the muon veto panels were installed at the BR2 site, their efficiencies were investigated by Céline Moortgat from Ghent University. The efficiencies were determined to be 84.1 $\pm$ 1.0% for the lower panel and 79.9 $\pm$ 0.9% for the upper panel [32]. Multiplication of these values results in a combined efficiency of 67.2 $\pm$ 1.1%, which is in rather good agreement with the value found here.

It should be noted that the event itself can also affect the determined fraction of triple coincidences. Although this is most likely, the vertical tower of signals in four NEMENIX cubes is not necessarily caused by the passage of a vertical muon. Therefore, the intrinsic fraction of coincidences between the tower of cubes and the upper and lower muon veto panel will already be lower than 100%.

**4.2.4 Vertical muon properties**

For the vertical muon events, the first property under investigation is the detector response of NEMENIX. Figure 4.11 shows the amplitude versus integral for each of the four signals within the events identified as a vertical muon event.

As is expected for all muons, the NEMENIX signals for vertical muons are located at high amplitude and high integrated charges. The average of the distribution lies somewhat
Figure 4.11: The NEMENIX detector response, plotted as the amplitude versus integral distribution for the signals building up vertical muon events.

higher compared to the more global selection of muon like events with a coincidence in the upper and lower muon veto panels, shown in the top plot of figure 4.3. This is seen, for example, from the fact that the tail towards the lower amplitudes and integrals is more dilute in the vertical muon plot.

An illustration of this same distribution per layer or, equivalently, per read-outboard of the NEMENIX detector is shown in figure 4.12.

The plots show that there are diffuse blobs in the amplitudes within all the boards. This effect can be traced back to the different saturation values of the channels, as discussed in paragraph 3.2.2 of the previous chapter. Because the signals originate from a combination of peaks on two channels, the effect of the different saturation values is sometimes cancelled out and, overall, the saturation regions are also smeared out into each other.

Remarkable in this figure of the response per board, is that the tail towards lower amplitudes only shows up in the distributions for the two outer boards. The events that contain such a low amplitude signal ($< 160$ PA) were selected and investigated in terms of their position in NEMENIX. Figure 4.13 shows the distribution of the vertical towers for these events.

It is seen that the vertical muon events that have a low amplitude signal almost exclusively occupy positions on the edge of NEMENIX. Therefore, this effect can be due to muons that have an angle which is slightly larger ($\geq 14^\circ$) than what is allowed for vertical muon events. These muons can enter (leave) the first (last) cube in the tower at
Figure 4.12: The distribution of the amplitude versus integral for the selection of vertical muon events, shown separately for each board of the NEMENIX detector.

Figure 4.13: The distribution in NEMENIX of vertical muon events that have one or more low amplitude signals.
the side instead of the top (bottom), due to which they only cross a smaller part of this cube. When this is the case, these muons deposit less energy in the outer cube(s), which results in the tail in the distributions in the upper and lower layer of NEMENIX. This feature is not seen for central positions, since such muon tracks with a slightly larger angle will also cross part of the neighbouring cubes. The requirement of isolation of the tower will consequently reject those events.

4.3 Clipping muons

Clipping muons are muons that hit a corner of NEMENIX and thereby create a signal in one of the edge cubes of this detector. To distinguish them from other electromagnetic particles, such as positrons for example, a coincidence with at least one muon veto panel is required.

4.3.1 Clipping muon event selection

The selection of clipping muon events is based on two criteria.

1. Topology. The event can contain only one cube with a signal. Furthermore, this cube must be located on the edge of NEMENIX.

2. Muon veto. There should be at least one muon veto panel with a signal. There is no distinction between the upper, lower, left or right one for the selection of clipping muon events.

The edge cubes are considered to be those cubes that have at least two of their planes at the surface of the detector. The edge cubes are the red coloured ones in figure 4.14. The other cubes, which are not coloured in this sketch, are referred to in the following as central cubes.

An example of a clipping muon event, selected by the method described above is given in figure 4.15.

4.3.2 Muon veto coincidence

As seen in section 4.1, of the events that fulfill the OR-case conditions, a relatively larger fraction has only one signal in NEMENIX compared to the events of the AND-case. This can be related to the orientation of cosmic muons that clip NEMENIX. It is expected
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Figure 4.14: The so-called edge cubes in NEMENIX.

Figure 4.15: Example of a clipping muon event, illustrated with the Event Viewer tool. The upper and right muon veto panel are triggered and a signal with a high integrated charge is found in an edge cube.
that these clipping muons have a relatively larger angulation with respect to the vertical, otherwise they would, when hitting one cube one the edge, also hit a second and even more cubes above or below this one. The larger angulation of the muon tracks explains the raised probability that the track crosses only one of the two horizontal muon veto panels.

Table 4.3 shows a study of the relative fractions of coincidences with the muon veto system for clipping muon events.

Table 4.3: Fractions of coincidences between the cube which represents the clipping muon in NEMENIX and the four muon veto panels. The upper part of the table presents triple coincidences, the lower part shows the total number of coincidences for each of the four panels. Strictly double coincidences, between a cube and one panel, are not included.

<table>
<thead>
<tr>
<th>MV panels</th>
<th>fraction of coincidences [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up and low</td>
<td>20.763 (0.436)</td>
</tr>
<tr>
<td>Up and left</td>
<td>2.841 (0.098)</td>
</tr>
<tr>
<td>Up and right</td>
<td>8.272 (0.185)</td>
</tr>
<tr>
<td>Low and left</td>
<td>3.774 (0.138)</td>
</tr>
<tr>
<td>Low and right</td>
<td>8.929 (0.199)</td>
</tr>
<tr>
<td>Left and right</td>
<td>0.164 (0.041)</td>
</tr>
<tr>
<td>Total up</td>
<td>56.302 (0.516)</td>
</tr>
<tr>
<td>Total low</td>
<td>59.496 (0.363)</td>
</tr>
<tr>
<td>Total left</td>
<td>9.072 (0.234)</td>
</tr>
<tr>
<td>Total right</td>
<td>22.473 (0.317)</td>
</tr>
</tbody>
</table>

The table shows some knowable features. For example, there are in general more coincidences between the cube in NEMENIX and the lower muon veto panel, than there are with the upper muon veto panel. This was also seen for the OR-case events and, as explained before, it is most probably due to the relative position of NEMENIX between the upper and lower panels of the muon veto system.

Looking at the triple coincidences between NEMENIX and two muon veto panels, the upper muon veto panel seems to have less coincidences with the left and right panels, compared to the lower muon veto panel. Again, this can be linked to the relative positions in the detector set up; the lower muon veto panel is slightly closer to the small vertical ones, than the upper muon veto panel.
Differences in the coincidence fractions are not only found between upper and lower panels, but there also seems to be an asymmetry between left and right muon veto panels. There are systematically more coincidences with the right muon veto panel than there are with the left one. Since their relative positions with respect to the NEMENIX detector and the two horizontal muon veto panels are practically the same, the origin of this asymmetry cannot be found here.

The effect might be due to different shielding conditions on the left and right side of the detector setup. The HDPE layers surrounding the detectors are equally thick, so these are not expected to affect the symmetry. Besides, they can efficiently stop neutrons, but they are not dense enough to capture the highly energetic cosmic muons.

One of the structures that can screen part of the cosmic muons are the concrete walls of the BR2 containment building. Concrete, in itself, has a rather poor shielding effect on cosmic muons, but since the walls are very thick, their influence is not negligible [37]. Secondly and more effectively, lead walls which are placed on the left and right side of the NEMENIX setup, also cause shielding of the cosmic muons. However, these walls are of the same thickness and should thus equally affect the cosmic muon distribution. Due to the lack of precise information on the thickness of the concrete walls, it cannot be concluded if their shielding effect is the origin of the left-right asymmetry in the coincidences.

### 4.3.3 Clipping muon rate

As was done for the other types of muon background, the rate of clipping muon events was determined by dividing the number of events with the time over which was counted. The clipping muon rates are illustrated per day in the left plot of figure 4.16. Their mean value is \(0.768 \pm 0.018\) Hz.

Also interesting to investigate is the fake rate of NEMENIX coincidences with the muon veto system. This can be done by comparing the rate of a coincidence between one of the edge cubes and the muon system, with the rate of a coincidence of a signal in one of the central cubes and a muon veto signal.

The rate of coincidences of the muon veto system with one of the central cubes is \(0.0370 \pm 0.0022\) Hz and is shown as a function of time in the right pane of figure 4.16. This rate is much lower than the clipping muon rate. Anyway, it is of the same order of magnitude as the rate of vertical muon events and should not be left indifferent for some cases of event reconstruction.
Figure 4.16: The rate of clipping muon events (left) and fake clipping muon events (right) for each day of data taking in the period under investigation.

These fake events can be the consequence of false coincidences of signals in the electronics, or they might also be a result of the intrinsic efficiency of the cube assemblies. It could, for example, happen that a muon crosses multiple layers of the NEMENIX volume, while it is only detected in one of the middle panels.

4.3.4 Clipping muon properties

The distribution of the clipping muon signals is plotted in terms of the signal amplitude and integral in figure 4.17. Compared to figure 4.11 of the vertical muon events, this distribution has much more events in the tail at low amplitudes and integrals.

The same distribution is shown per layer of NEMENIX, in figure 4.18.

For the clipping muons, the tails in the amplitude-versus-integral distribution are seen in all the boards. This corresponds to what is expected, since the clipping muons sometimes cross the full diagonal of an edge cube, or they can equally as well travel only a very small part of a cube. In contrast to the case of vertical muons, this effect is now not limited to the outer boards, but can occur in any of the four layers.

An illustration of the detector response for the fake clipping muon events, is shown in figure 4.19.

The relative number of events in the tail of the distribution is somewhat higher for this type of events. The low amplitude events could correspond to EM signals, which accidentally showed a coincidence with the muon veto system and therefore appeared as a muon induced event. However, also fake clipping muon events with high amplitude
Figure 4.17: The NEMENIX response for the clipping muon events.

Figure 4.18: The NEMENIX response for the clipping muon events, shown per layer of NEMENIX or, equivalently, per electronics board.
signals are found. These events most probably correspond to a cosmic muon event in which the surrounding PVT cubes of the fake signal cube did not correctly respond to the passing of a muon.

### 4.4 Reactor-off versus reactor-on data

In the previous sections of this chapter, all investigations and calculations were performed on a set of reactor off data files which include the measurements of the 14th till the 28th of August 2014. The results presented above, also have to be compared with results from an analysis that uses reactor-on data.

The comparison has shown that all the distributions of the events in amplitude, integral and other properties, which are shown in the figures of the previous discussions, have the same qualitative features for reactor-off and reactor-on data.

However, the rates of the AND-case and OR-case muon veto coincidences, as well as the vertical muon and clipping muon rates, are systematically higher for the analysis with reactor-on data. This is seen from table 4.4, where both the rates for reactor-off and reactor-on data are shown for the different classes of muon background that were discussed in the course of this work.

The consistent difference in rate is remarkable and rather unexpected, since the running of the nuclear reactor should not affect the amount of cosmic muon background. The only expected differences lie in the number of neutron and EM signals.
Table 4.4: A comparison of the rates of the different types of muon events for reactor-on and reactor-off data.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Rate ON [Hz]</th>
<th>Rate OFF [Hz]</th>
<th>Increase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND-case</td>
<td>1.190 (0.014)</td>
<td>1.067 (0.021)</td>
<td>11.528</td>
</tr>
<tr>
<td>OR-case</td>
<td>1.462 (0.034)</td>
<td>1.343 (0.034)</td>
<td>8.861</td>
</tr>
<tr>
<td>Vertical muons</td>
<td>0.0281 (0.0014)</td>
<td>0.0248 (0.0013)</td>
<td>13.306</td>
</tr>
<tr>
<td>Clipping muons</td>
<td>0.868 (0.013)</td>
<td>0.768 (0.018)</td>
<td>13.021</td>
</tr>
<tr>
<td>Fake clipping muons</td>
<td>0.0426 (0.0012)</td>
<td>0.0370 (0.0022)</td>
<td>15.135</td>
</tr>
</tbody>
</table>

The third column of table 4.4 shows the increase for the reactor-on rates as a percentage of the reactor-off rates. This percentage is very similar for all the types of events, pointing into the direction of a systematic effect, which would rather depend on the calculation method for the rates than on physical effects.

A possible explanation for the increase might be that the rate calculation is slightly biased by the number of detected neutrons. As mentioned before, only those events which are within a small time window around a neutron signal are stored. When the nuclear reactor is running, a significantly higher number of neutrons is expected to be seen in NEMENIX. Therefore, per fixed measuring time, more data will be kept for the reactor-on periods. In principle, this should not affect the rates, since only the time intervals over which events were stored are summed up. However, it can not be fully excluded that the manipulation of the data set creates some unforeseen effects that slightly bias the calculation of the rates.

There is a second possible explanation for the difference in the rates, that does not involve the rate calculation method, but would be induced by the muon selection criteria. If a filtering of the NEMENIX peaks with a threshold at 60 PA does not only select real cosmic muon induced peaks, but also preserves some EM signals, then the relative number of muon signals would also be higher for reactor-on data. To test this hypothesis, a reevaluation of the rates was performed for an analysis with an amplitude threshold of 75 PA for the selection of NEMENIX peaks. It was found that the increases in the percentages for reactor-on data with respect to reactor-off data were very close to the ones presented in table 4.4. This weakens the probability that the rate increase is due to an EM component in the selection of peaks.

The rates of muon coincidences in the NEMENIX set up have also been investigated for other periods of reactor-on and reactor-off data by Andrew Deeble from Oxford University. For his investigation, an analysis code was used that is independent from
the one developed for this thesis. The selection criteria for muon signals were chosen independently, as was the method for the calculation of the rates. However, the results of this analysis also show a larger rate of cosmic muon coincidences for reactor-on data, compared to the reactor-off periods [38].

4.5 Other forms of muon background

Of course, vertical and clipping muons are not the only forms of muon background for the SoLid experiment. This section sums up some of the other types of cosmic muon events and gives some suggestions for further investigation.

4.5.1 Stopped Muons

Since muons have a finite lifetime, they decay at some point on their way from the cosmos to and/or through Earth. It is thus also possible that muons are stopped and decay in the NEMENIX detector. This would manifest itself as an incomplete track of signals through a muon veto panel and some PVT cubes that stops before it leaves the detector.

Within the course of this thesis, a basic search for stopped muon candidates was performed. Because of the limited amount of resulting stopped muon candidate events, a further analysis of this type of background was discarded.

The first approach was to search for stopped vertical muons. This does not require an extensive determination of the (expected) track and makes a search very straightforward. To select events in correspondence with stopped vertical muons, the following requirements should be satisfied:

- The event should only contain a signal in the upper muon veto panel and no signal in the lower muon veto panel.
- A small number of NEMENIX signals is required, forming a vertical tower of 1, 2 or 3 cubes.

Since a minor part of the full vertical muon towers in NEMENIX also only has a signal in the upper muon veto panel (cf. section 4.2), it can be discussed if these events also belong to the category of stopped vertical muons. However, one can not be sure if the muon actually stopped in the last cube or if the lower muon veto panel falsely did not
respond to the outgoing muon. To keep the search conservative, these events were not selected as stopped muon candidates.

Also a more general search was implemented, based on a selection regarding the position of the involved cubes. The first search looked for events with

- a signal in the upper muon veto panel and no signal in the lower muon veto panel,
- some signals in NEMENIX, in the upper 2 or 3 layers.

Unfortunately, a large part of the resulting selection of events was difficult to distinguish from clipping muons. Moreover, also events with muon tracks which come in at the top and leave at a side of NEMENIX were selected with this approach. To make sure none of these events were selected, stricter conditions were imposed on the event topology. Events with

- a NEMENIX signal in one non-central cube and in one central cube,
- or with a NEMENIX signal in one non-central cube and in two central cubes

were selected. Here, the definition of central cubes is slightly different from the one used in the section dealing with clipping muons; the term central cubes now refers to those eight cubes which are located in the center of NEMENIX and are not part of the surface of the detector. The non-central cubes are all the other ones, which have at least one of their planes at the surface of NEMENIX.

The main problem for the search for vertical and general stopped muons was that the selection criteria were too strict to have a significant amount of surviving events. The limited dimensions of NEMENIX are the main origin of this shortage.

The search for stopped muons should be easier with a larger detector module, such as SM1. The use of simulations might also be of great help. One could then first investigate the probability to have a cosmic muon that is stopped in the detector. Further on, the signature of such an event in the detector can be determined. This information could later benefit the optimization for a stopped muon search.

4.5.2 Horizontal muons

Another category for the background analysis can be the horizontal muons, which are the opposite of the vertical ones. One would now have to search for a row instead of a
column of cubes. In this case, a combination of 1 x (y) fiber with 4 y (x) fibers needs to be searched for.

There are three main difficulties for the search for horizontal muons. First of all, the intrinsic number of horizontal cosmic muons is very low. This is, for example, clear from the distribution describing the intensity of cosmic muons as a function of their angulation from the vertical. As mentioned before, this distribution follows a $\cos^2 \theta$ law. The number of muons which will horizontally impinge on the detector will thus be very limited.

Moreover, the shielding by the surroundings will also be much more effective for these horizontal muons. This is due the fact that they have to travel significantly more material before they can reach the detector. Note, for example, that lead walls with a thickness of approximately 40 cm are placed on the left and right side of the detector. It is thus very probable that a horizontal muon investigation will suffer from extremely low statistics.

The third point of attention is the fact that for the surviving horizontal muons, one will have to deal with a high level of saturation of the electronics. This is a consequence of the horizontal muons traveling parallel to a fiber. The result is that a large number of photons gets collected by this one fiber, which will immediately saturate the connected MPPC.

Like it was done with the vertical muons and the upper and lower muon veto panels, the selection of horizontal muons could be used to test the efficiency of the left and right muon veto panels.

### 4.5.3 Diagonal muons; muon tracker

To have a full selection of the cosmic muon background, a tracking algorithm can be applied. This tool could then identify and reconstruct all possible forms of muon tracks, independent of their direction and angulation.

A useful check of the detector’s performance can be provided by an investigation of the relative intensity of muons per angulation. A comparison of the results of such an investigation with the known distribution of cosmic muons, can give information on the detection efficiencies of different parts of NEMENIX, shielding effects of the environment, etcetera.
Chapter 5

Outlook and Conclusions

Recent experiments have shown anomalies in the world of neutrino physics that might be induced by the existence of a sterile neutrino. The SoLid experiment is one of the novel projects that will investigate the existence of such a new type of neutrino by conducting a very short baseline reactor neutrino experiment.

The SoLid experiment started data-taking in 2013 with a prototype detector, called NEMENIX. This was done to gather useful information about the detector’s performance, maintenance, read-out, etcetera, before starting the construction of the large-scale detector modules. The NEMENIX prototype was also used to investigate the backgrounds present at the experimental site.

One type of background for the SoLid experiment are cosmic muons. These energetic particles can penetrate thick layers of shielding and therefore can not be stopped from impinging on the detector. For this thesis, different forms of cosmic muon background that are detected by NEMENIX were studied.

The research started with a general selection of muon induced events, based on the coincidence of signals in NEMENIX with signals in its muon veto system, in section 4.1. From this investigation, it was seen that a selection of events that have a signal in the upper and lower muon veto panels, biases the NEMENIX response in the direction of events with mostly four or five triggered cubes. On the other hand, when only one of these two panels is triggered, the event clearly contains a smaller amount of lit cubes. The latter case can be interpreted to correspond to muons which hit a corner of NEMENIX, the former case indicates longer tracks of cosmic muons that travel through the full detector.

Following the clues from the first section, two cases that are more specific in event topology, were analyzed and discussed in sections 4.2 and 4.3. This concerns respectively
the vertical muon and clipping muon events, that are both considered to represent a significant fraction of the cosmic muon background.

From the results presented in the first three sections of chapter 4, it can be concluded that all of the studied muon events produce signals that tend to lie in the saturation region of the electronics. A rough selection, based on the application of thresholds on the amplitude and integral of the signals, should be able to filter out a large part of the cosmic muon background, without losing too much of the signals of interest, that are related to inverse beta decay interactions.

From sections 4.2.4 and 4.3.4, it is seen that signals with an amplitude and integral that are slightly below the saturation region can often be linked to a muon that does not cross a full PVT cube of the NEMENIX detector, but only crosses a smaller part of this cube and therefore deposits less energy.

For each type of the above-mentioned events, the rates were also estimated. A summary of these rates is given in table 4.4, which shows values for reactor-off as well as reactor-on measurements. It was found, as discussed in section 4.4, that the rate is systematically higher for reactor-on periods, compared to the reactor-off periods. For a selection of muon induced events, however, this should not be the case, since the running of the reactor only increases the electromagnetic and neutron backgrounds. A possible explanation for this discrepancy might lie in the calculation method for the rates, or it might originate in a erroneous selection of the muon signals. Another remarkable feature of the calculated rates is that they show a common pattern in their rate-over-time plots. It has so far not been possible to determine the cause of this effect. One hypothesis is that this could be linked to temperature variations.

In parallel with the investigation of the muon background, some parts of the development of a new, more general framework structure for the data analysis of the SoLid experiment, were also conducted. The structure of this code, referred to as the Ghent NEMENIX Framework, is detailed in chapter 3. Within this framework, also an Event Viewer tool, useful for the visualization of an event, was developed. This tool allows one to interpret particle interactions with the NEMENIX detector and the surrounding muon veto panels in a simple and intuitive way.

Recently, in May 2015, the decision was taken to merge the existing analysis codes and novice framework structures into one common code, of which the basis was developed by researchers from the University of Bristol. This framework, called Saffron, will be adjusted and improved so that it can serve all the ongoing and future analyses of the full SoLid collaboration.
For now, the data taking with NEMENIX has stopped. Some of the analyses of the NEMENIX data are still ongoing, but most of them are concluded. Currently, the largest analysis effort goes to the investigation of the data gathered by the first large-scale submodule (SM1) of the SoLid detector.

In the next months, the construction of a second submodule of the SoLid detector will start. This will enable the experiment to take data with two separate detector modules, placed at different reactor-detector distances. In this way, both the rate and shape of the reactor antineutrino flux can be evaluated, which will allow a very good determination of the limits on the existence of the sterile neutrino.
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