Improving the IceCube sensitivity with a wavelength shifting optical module

Simon Apers

Supervisor: Prof. dr. Dirk Ryckbosch
Counsellor: Sander Vanheule

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Engineering Physics

WE05
Chairman: Prof. dr. Dirk Ryckbosch
Faculty of Engineering and Architecture
Academic year 2013-2014
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Acknowledgments

The following are supposedly the last words I write of this thesis. I would like to devote them to some people that helped me throughout the past year, providing either academical or moral support.

Starting with the former - in the first place that would be Sander Vanheule, who seemed to have a gift for perpetually creating both time and answers. Secondly I must thank Jan, Simon, Céline and Jonathan, fellow thesis students always there for advice and company. Lastly I want to thank Professor Ryckbosch and the rest of the Ghent IceCube group.

In a moral sense I received relentless support for the last five years by my family and girlfriend, whom I will always stay grateful.

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Simon Apers,
2 June 2014
Synopsis

In chapter 1 background is provided to the subjects, methods and aims of this thesis. Section 1.1 provides a concise review of the history of particle physics and a recapitulation of the Standard Model and more general neutrino physics. Chapter 2 goes over the experimental setup. In section 2.1 the used muon trigger is explained and in section 2.2 the principle of using wavelength-shifting technology to collect Cherenkov light is disclosed. Section 2.3 describes the calibration of both the trigger and the readout of the setup. An analysis of the trigger distribution is described in section 2.4. In chapter 3 the simulation of the setup is presented. Section 3.1 explains the different abstractions made and the general outline of the simulation. The main outcomes of the simulation are shown in section 3.2. Finally chapter 4 summarizes the measurements and results of the full setup. The origin of the detected light is checked in section 4.1 and a scan over the scintillator responses is described in section 4.2. Section 4.3 presents the Cherenkov light measurements and in section 4.4 different cuts on the measurements are performed and analysed.
Improving the IceCube sensitivity with a wavelength shifting optical module

Simon Apers

Abstract—The research presented in this paper is aimed towards investigating the feasibility of using a wavelength-shifter as sensitive surface for the detection of Cherenkov light. Thereto an experimental setup was used in conjunction with a Geant4 simulation of the setup. An extensive calibration allowed to unambiguously detect Cherenkov radiation and compare efficiencies between different measurements, invigorated by the simulation. Additionally on basis of the setup a new method is proposed to shed light on the otherwise concealed efficiency of the used muon trigger.

Index Terms—WLS, Cherenkov detector, IceCube, Geant4.

I. THE ICECUBE NEUTRINO OBSERVATORY

The IceCube Neutrino Observatory is a neutrino telescope based on the South Pole, using approximately one cubic kilometer of ice as its detection medium. By capturing Cherenkov radiation produced by the crossing of charged particles, traces are found concerning the origin of the highest energy cosmic rays. In its current state it allows the indirect detection of $10$ to $10^{15}$ GeV neutrinos. These thresholds represent the resolution of the detector, set by the efficiency of Cherenkov light capture. This is the reason why IceCube is constantly seeing to improve its detection instrumentation, leading directly to the motivation of this research.

II. DETECTION OF CHERENKOV RADIATION: OPTICAL MODULES

Currently IceCube uses 5160 Digital Optical Modules (DOMs) implanted in the ice to detect Cherenkov light. These are glass spheres housing large photocathodes as their active surface. The capture efficiency\(^1\) of photocathodes is very high but they are costly and have a high noise rate, both of which scale with the photocathode size. These downsides can become an obstruction if one wants to improve the IceCube resolution by enlarging the photocathode surfaces. An alternative has been suggested based on passive wavelength-shifting materials (WLS), so-called Wavelength-Shifting Optical Modules (WOMs). A design published by Lukas Schulte is shown in figure 1. The principal idea is to separate light collection and light conversion. Collection ought to be carried out by a surface as large as possible whereas conversion happens by a photocathode and thus needs to have a minimal surface for the above-mentioned reasons. In the case of a WOM the light collection is performed by a wavelength-shifter, absorbing photons and re-emitting them at a larger wavelength. Total internal refraction confines a large part of the photons, pushing them to the sides of the WLS where they are bundled and led to a photocathode of much smaller size. The noise rates are expected to be a factor of 80 lower than is the case for DOMs. This research aims at experimentally endorsing the usage of a WLS to capture Cherenkov light.

\(^1\)The capture efficiency of a device denotes the probability with which an incident photon produces a detectable signal

![Fig. 1: Design of a WOM [1].](image-url)
III. WOM SETUP

The setup used consists of a 168 l water tank containing a 10 cm x 0.5 cm x 80 cm WLS bar placed horizontally at one fifth of the tank height. Above and below the tank an array of eight scintillator bars is placed, each bar read out by a different photomultiplier tube (PMT). The arrays serve as a trigger for passing muons. Upon receiving a trigger signal both sides of the WLS are read out by two PMTs penetrating the tank both left and right. For comparison, all measurements performed are repeated for the tank without WLS, only capturing photons directly incident on the two small WLS PMTs.

IV. WOM INQUIRY - SIMULATION

A simulation of the setup is created using the Geant4 toolkit. With the geometry and materials implemented, an incident muon source is created, closely approximating the setup conditions. The dominant processes are shown to be muon ionization, the Cherenkov effect and scintillation in the water. As a consequence the only particles included are muons, electrons and photons. The wavelength-shifting process inside the WLS was not modeled but replaced by a Monte Carlo calculation based on published capture and emission probabilities. It was found that an incident photon on the WLS is detected with an efficiency of 0.04% whereas this is 13% for incidence on the bare PMT. This is a consequence of the small absorption window of the WLS and mismatch of its emission spectrum with the PMT used. Specifically for the setup this decrease is easily compensated by the amount of photons incident on both surfaces, being almost a factor 900 greater for the WLS than for the small photocathodes. Due to this compensation the amount of photoelectrons picked up per passing muons is found to be 1.79PE for the setup with WLS, indicating a 83% efficient detector, versus 0.61PE without WLS, indicating a 54% detection efficiency.

With the most important mechanisms programmed, this simulation could in the future be used to simulate more realistic situations such as the implementation of WOMs in IceCube.

V. CALIBRATION OF THE SETUP

The setup uses two sets of PMTs, one for the readout of the trigger scintillator bars and one for the readout of the WLS bar. As the scintillator PMTs are merely used for triggering purpose, their exact response is of no interest and only the triggering rate is calibrated. This rate is set by the voltage over the PMT and the threshold check performed by the CFD readout module, producing the actual trigger. Ultimately all rates were set between 2.3 Hz and 3.5 Hz, well above the PMT noise rate and below the expected muon flux being 10 Hz per scintillator. Concerning the response of the WLS PMTs a more thorough analysis is performed where also the exact amount of charge created was measured. For the calibration a laser source with variable intensity is used. Due to the statistical nature of the PMT working, large sets of repeated measurements have to be performed to which a general PMT response can be fitted, revealing the PMT characteristics. Figure 2 shows a fit to the response of a laser-illuminated PMT for a $2 \times 10^5$-event measurement. The discrete PE peaks are found back and a well-defined correlation between amount of photoelectrons created and intensity of the laser source was observed. The most important measure following from the fitting is the parameter $\mu$, indicating the mean amount of photoelectrons per trigger, thus indicating the efficiency of the measurement.

The full trigger consists of an array above and an array below the setup, each housing 8 scintillators individually read out using a TDC module. If two scintillators are triggered, an estimate of the direction of the passing muon can be made. Figure 3 shows the angular distribution of the caught muons, closely approximating the expected cosine-square distribution. The distribution however is shifted over 5.73°, most likely caused by the upper array not lying perfectly above the lower array.

2 When a PMT effectively captures a photon a photoelectron is generated, afterwards amplified to a detectable signal.

3 The efficiency of the detector is calculated using a Poisson distribution with $\lambda = 1.79$. This way the chance of zero photoelectrons, $P(0)$, becomes 17%, leading to a 83% efficient detector.
VI. RESUME OF THE MEASUREMENTS

Before going into the final measurements it is assured that the light picked up inside the tank originates from the Cherenkov effect. Identical measurements in a full and an empty tank showed that the mean amount of photoelectrons $\mu$ for the former is a factor of several hundred more than for the latter. The simulation already showed that 80-90% of the light created in the full tank is caused by muon Cherenkov light hence proving the origin of the detected signal. Final measurements were performed on the tank with and without WLS, both for a full and empty tank. According to the simulations the measurements with WLS should show a higher $\mu$, as do the measurements of the full tank. The fitted values are shown in Table I and show the expected tendencies. The simulated values for the different measurements are a factor 23 to 33 higher, presumably caused by losses and inefficiencies not taken into account (e.g. refraction losses at the WLS and PMT surfaces).

A further analysis of the measurements is performed by only selecting the events in which coincidence between both trigger planes was found back. The coincidence demand is expected to cut out the noise trigger signals and the events in which a muon is absorbed in the tank or exits sideways, leading to an increase of $\mu$. This was not found back. An explanation is proposed based on the assumption that each trigger signal is unambiguously created by a muon, thus neglecting e.g. noise triggers. The lack of correlation can then be traced back to failure of the lower trigger to detect the muon. The measure for this failure is the trigger efficiency. Based on the assumption made, the trigger efficiency of each of the lower scintillators can be calculated. For each upper trigger signal a muon will either cross one of the lower array scintillators or leave the setup sideways, the ratio of which was predicted using the simulation. By then looking at the detected amount of muons in the lower scintillator versus the expected amount, the efficiency is calculated. Per calculation only one upper and one lower scintillator is used so the calculation can be repeated eight times. Figure 4 shows the results. Instead of the expected flat curve, a cosine-like dependency of the efficiency on the angle between upper and lower scintillator was found back. This is caused by an anisotropy in the scintillator efficiency or an error in the calculation but could not be immediately resolved.

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TABLE I: Light capture $\mu$ from the fitted measurements.
VII. CONCLUSIONS

It has been proven possible to detect Cherenkov light using a WLS and the simulation showed it to be promising. Especially the freedom in geometry allows an efficient light capture, compensating for the smaller capture probability of the WLS. Furthermore the individual readout of the triggers lead to a more founded interpretation of the measurements, rectifying multiple false assumptions.

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Glossary

CE Capture efficiency.
CERN European Organization for Nuclear Research.
CFD Constant fraction discriminator.
DAQ Data acquisition.
DOM Digital Optical Module.
GEANT4 Geometry and tracking toolkit.
PMT Photomultiplier tube.
QDC Charge-to-digital converter.
SLAC Stanford Linear Accelerator Center.
TDC Time-to-digital converter.
WLS Wavelength-shifter bar.
WOM Wavelength-shifting Optical Module.
Chapter 1

Introduction to neutrinos, their detection and IceCube

1.1 Theoretical background

Neutrinos are descendants of the Standard Model. This Standard Model serves as the theory describing subatomic structures and nuclear interactions, comprising the electromagnetic, weak and strong forces. It is sometimes called the “theory of almost everything”, referring to its success in predicting a wide variety of experimental results. In order to fully understand the importance and situation of the Standard Model, some background needs to be provided, specifically on the history of particle physics; the branch of physics sprouting from the assumption that all matter and interactions are made up of elementary particles.

1.1.1 Particle physics epitome

Before modern particle physics came up, there was a period of classical particle physics, roughly from 1897 to 1932. It started with the discovery of the electron by J.J. Thompson [1]. The deflection of cathode rays by a magnetic field suggested they contained charge. This lead to the idea that the rays in fact were streams of particles, first named *corpuscles*. Thompson was able to determine the charge-to-mass ratio of these particles. As it was enormously greater than for any other known ion, he figured they had to have a tiny mass. Atoms as a whole are electrically neutral, that is why Thompson figured that electrons were suspended in a positively charged paste (as the plums in a pudding). This idea was abandoned rather fast thanks to Rutherford’s famous scattering experiment [2]. This experiment showed that atoms had a small positively charged core, the nucleus, which was surrounded by electrons. The nucleus of the lightest atom (hydrogen) was named proton. Thereafter a new problem rose, namely that the next heavier element, helium, weighs four times as much as hydrogen, and the following one, lithium, seven times as much. In 1932, Chadwick [3] resolved this issue by the discovery of the neutron, a neutral twin to the proton. The neutron discovery is the last major event still ascribed to the so-called classical period of particle physics, revolving around the electron, the proton and the neutron.

The period of modern particle physics started around 1930. The first event ascribed to the period was the discovery of the positron, the antiparticle of the electron. It was discovered by Carl David Anderson in 1933 through the examination of cosmic rays\(^1\) [4]. The positron was the first evidence of antimatter. Five years earlier, Dirac already published a paper [5] that introduced the famous Dirac equation, a unification of quantum mechanics, special relativity and electron spin. From these equations it followed that, next to the solution containing negatively charged electrons with positive energy, also a solution containing positively charged electrons with negative energy was possible.
electrons with negative energy was possible. For a while Dirac persuaded the idea that the proton was actually the positively charged electron. However, the great difference in mass and Robert Oppenheimer’s argument, saying that if Dirac’s assumption were true then the hydrogen atom would rapidly self-destruct [6], made Dirac reconsider his case. As a consequence, Dirac published a paper in 1931 predicting the existence of an entirely new particle, the positron [7]. In 1940, Dirac’s theory of “negative energy particles” was reinterpreted by Stuckelberg and Feynman and replaced by the notion of “antiparticles”. Antiparticles are different particles, not just different states, also having a positive energy. They predicted that every particle should have its antiparticle. This was invigorated by the discovery of the antiproton in 1955 [8] and the antineutron the following year [9].

The examination of cosmic rays not only lead to the discovery of the proton. Their further examination, again by C.D. Anderson, lead to the discovery of the muon in 1937 [10]. It was determined to have a mass somewhere between the electron and the proton, hence its initial name mesotron (prefix meso- adopted from the Greek word for “mid-”). For a while it was believed that this particle, the muon, was the particle mediating the strong force. Such a particle was predicted in the theory of Hideki Yukawa, published four years earlier [11]. In the following years, as the particle was studied more thoroughly, it showed some disturbing discrepancies. The mass was slightly above Yukawa’s prediction and the lifetime was wrong. It would take ten more years for a solution to come up.

In 1947, renewed studies by Cecil Powell and his co-workers showed that the muon was not the only middle-weight particle contained in cosmic rays. A new particle, the pion, was discovered [12]. This particle showed a much stronger interaction with the nucleons and was pretty soon determined to be the particle predicted by Yukawa. This placed the muon in a rather peculiar role, seemingly unnecessary in the present theory (as put by Isidor Rabi - “Who ordered that?”). For completeness, the discovery of the kaon that same year should be mentioned [13]. This discovery was also thanks to the use of cosmic rays.

The neutrino was first detected experimentally in 1956 by Fred Reines and Clyde Cowan [14]. Its theoretical description however goes further back. In 1911 a discrepancy occurred in the electron energy spectrum, emitted during beta decay. The spectrum was predicted to be mono energetic, owing to the conservation of energy. However when measured, by Lise Meitner and Otto Hahn, the spectrum was shown to be continuous. Bohr’s explanation back then was that the conservation of energy was only true in a statistical sense and could be violated in any given decay. Some years later, between 1920 and 1927, this explanation was disproved by Charles Drummond Ellis and James Chadwick as they showed that the decay spectrum is truly continuous. It was not until 1930 that Wolfgang Pauli, in a letter, presented his idea that an additional particle was emitted. He called it the “neutron”, which would later be renamed to “neutrino” by Enrico Fermi. In 1934 Fermi published his model of beta decay, including the neutrino [15]. The reason why it was not observed before is due to its extremely weak interaction with matter, which is usually the sole way to detect a particle. As mentioned, it took until 1956 to experimentally detect it and confirm the ideas of Pauli and Fermi.

The following years bring a big evolution in detector and accelerator technology, leading to new experiments next to the well known and performed cosmic ray ones. One such major accomplishment was the invention of the bubble chamber by Donald A. Glaser, in 1952 [16]. This new technology paved the way to the discovery of many new particles, most of them unstable and strongly interacting. Amongst them were the delta (∆) and sigma (Σ) particle, both hadrons. The belief that all newly discovered particles were independent particles was becoming more and more difficult to hold. It was then that the first suggestions and ideas were made towards describing some sort of underlying structure, requiring again smaller building stones.

The first experimental sign for a nucleon substructure was found by Robert Hofstadter. His electron scattering experiments on protons provided the first evidence for a proton substructure
1.1. THEORETICAL BACKGROUND

Theoretically, the first steps towards a new theory were made independently by Murray Gell-Mann and Yuval Ne’eman. They proposed a particle classification system known as the Eightfold Way, based on SU(3) symmetry. It classifies baryons and mesons in a scheme, as shown in figure 1.1, assigning to each of them a different set of quantum numbers. The principles of the Eightfold Way could also be applied to the spin-3/2 baryons, forming a decuplet (figure 1.2). This decuplet lead them to the prediction of one last particle to complete the scheme, the omega ($\Omega^-$), detected in 1964, confirming their theory. The explanation of this ordering would later be explained by Gell-Mann and George Zweig [18, 19]. They introduced the concept of up, down and strange quarks, massive spin-1/2 particles with a fractional charge. Originally this concept only served to perform the classification but in 1969 the Stanford Linear Accelerator Center (SLAC) could experimentally verify this. From then on, no longer the hadrons but the quarks were considered to be “elemental”. Each baryon consists of three quarks whereas the mesons only consist of one quark and one antiquark. In this classification, the newly discovered particle $\Omega^-$, is made up of three $s$ quarks with parallel spins and vanishing orbital angular momentum. As the Pauli exclusion principle requires each wave function to be antisymmetric, there must have been another (hidden) quantum number. This lead to the concept of quark colour, published in 1972 by William Bardeen, Harald Fritzsch and Gell-Mann [20]. It was this publication that formed the foundation of quantum chromodynamics (QCD).

The quark model had provided an explanation for the Eightfold Way and correctly predicted the experimental results of the SLAC deep inelastic scattering experiments. One of the major remaining problems however was the absence of (experimental evidence of) free quarks, they seemed to be confined to their parent hadrons. This was one of the reasons withholding the model from being generally accepted. This changed with the so-called “November revolution”. This revolution was introduced by the discovery of the psi meson in 1974, independently by Samuel C.C. Ting and Burton Richter [22, 23]. What was so special about this particle is its lifetime, which was about a thousand times longer than any other similar particle’s lifetime. For many physicists this was a clear indication of new physics at work. It was the introduction of a new quark, the charm quark and antiquark, that provided an explanation. This name had already been introduced some years before by Bjorken and Glashow [24]. The November revolution was soon followed by the discovery of a fifth and sixth lepton, the tau and its neutrino, and a fifth quark, the beauty or bottom quark. Quite straightforwardly a sixth quark, the top or truth quark, was predicted. Due to its extraordinarily large mass, the experimental discovery of the top quark would only find place in 1995, at the Tevatron.

The theory explaining beta decay, proposed by Fermi in 1933, treated the process as a contact interaction. This way no mediating particle was needed, such as is the case in Yukawa’s theory of strong interaction. Now it is known that beta decay is the result of weak interactions, which
are indeed of extremely short range. This explains why the Fermi model held up that long. However, it was known that the model failed at high energies, creating a necessity for a mediating particle after all. The first real prediction of the mass of the new particle, named an intermediate vector boson, was thanks to Abdus Salam, Sheldon Glashow and Steven Weinberg in the late 1960’s [25, 26, 27]. They proposed a unification of the electromagnetic and the weak force, named the electroweak theory. The theory is based on three (contrary to only one predicted) intermediate vector bosons, two charged ($W^\pm$) and one neutral ($Z$). The experimental discovery of these particles is ascribed to CERN (European Organization for Nuclear Research), specifically to the group of Carlo Rubbia [28, 29]. In the span of half a year all three the particles were found experimentally, their masses agreeing well with those predicted.

As mentioned, Yukawa’s theory predicted the pion to be the mediator of the strong force. With the discovery of the heavy mesons, this could no longer hold as this would imply that nucleons could also exchange these heavier particles. A new approach was suggested by Gell-Mann, assuming the strong force to occur at the quark level rather than at the nucleon level [30]. The mediator is an electrically neutral particle called the gluon, referring to its glue-like function in a hadron.

It was during the 70’s that the so-called Standard Model would reach its final form.

### 1.1.2 Standard Model

The Standard Model of particle physics is the framework describing the electromagnetic, weak and strong nuclear interactions. It describes the entire subatomic world by means of 12 elementary particles, 4 kinds of gauge bosons mediating the interactions, and 1 Higgs boson. With the discovery of the Higgs boson in 2012, all constituents of the model have been discovered. Figure 1.3 shows a timeline summarizing the discovery of each of them. The particles are divided into families (classified) on different levels. The first classification is based on whether the particle is a fermion (spin-1/2) or a boson (spin-1). Fermions are particles that have a unique set of quantum numbers, individually occupying a place in phase space. Roughly said no two fermions can be at the same place at the same time. This principle is called the Pauli exclusion principle. It is the fermions that make up matter, they consist of 12 elementary particles. Bosons are of a fundamentally different nature, they mediate the forces. Different bosons can occupy the same set of quantum numbers.

The 12 fermions are further divided into quarks and leptons, depending on how they interact or equivalently what their charge is.

- **Quarks** come in six types; there are up, down, charm, strange, top and bottom quarks. They bind together to form trios called baryons, consisting of three quarks or three anti-quarks, and duos called mesons, consisting of a quark and an anti-quark. Collectively these are called the hadrons, derived from the Greek word hadros meaning “thick”. This points to the fact that they clump together and form larger particles. A last property ascribed to quarks is colour (or colour charge). Each quark is either red, green or blue. No real colour is perceived, it is merely called that way because of its nature of combining into colourless triplets (red plus green plus blue) or doublets (red plus antired etc.). Colour allows to describe the fact that no single quarks have been observed, they only occur in colourless combinations.

- **Leptons** also come in six types, namely the electron, muon, tau, electron neutrino, muon neutrino and tau neutrino. The first three are charged leptons and hence interact mainly electromagnetically. The last three leptons are neutrinos, they are chargeless and therefore only interact via the weak nuclear force. Leptons do not bind, explaining their name, meaning “thin” in Greek.
1.1. THEORETICAL BACKGROUND

Figure 1.3: Timeline showing the years from concept to discovery of the different Standard Model constituents [31].

Each of the fermions belongs to one of the three so-called generations. The up and down quark, the electron and its neutrino make up the first generation and so on. All ordinary matter is made up of particles from the first generation. The other two generations only occur in very high-energy environments. Lastly, every fermion has an antifermion, it has the same mass but opposite electric charge and colour. The fact that each of the 12 fermions exists both as a particle and an antiparticle, combined with three possible quark colours, leads to the Standard Model comprising 42 individual, distinguishable fermions.

The gauge bosons are defined as the mediating particles of the strong, weak and electromagnetic interactions.

- **Photons** are the particles exchanged during electromagnetic interactions between charged particles. There is only one type, which is massless, chargeless and has an unlimited range ($1/r^2$-law). Quantum electrodynamics (QED) is the theory describing their functioning.

- **Gluons** bind together the different quarks, mediating the strong force. There are eight types, consisting of two, four or six colours or anti-colours. The theory describing the interaction between quarks and gluons, dependent on their colour, is called quantum chromodynamics (QCD). As gluons also carry colour charge and therefore mutually interact, their range is limited.

- The $W^+$, $W^-$ and $Z$ boson carry the weak force. Contrary to the the previous bosons they have a large mass, limiting their range. As the two $W$ bosons carry charge,
they also couple electromagnetically.

The electromagnetic interaction and the weak interaction can be interpreted as two aspects of the same interaction: the **electroweak interaction**. Its discovery is ascribed to Abdus Salam, Sheldon Glashow and Steven Weinberg [25, 26, 27]. The last particle, completing the Standard Model, is the Higgs boson. It has a mass but no spin, electric charge or colour. The Higgs mechanism is responsible for the mass of the elementary particles. Despite the fact that the Standard Model is the most successful theory of particle physics to date, it is not perfect. First of all it is inherently an incomplete theory, lacking the explanation of most notably

- gravitation. An approach has been taken of adding a new particle, the graviton, to the Standard Model but for now this has not been successful. Moreover the Standard Model is widely considered to be incompatible with the theory of gravitation, general relativity.

- dark matter and dark energy. A large portion of the energy present in the universe is ascribed to dark matter. The Standard Model does not provide any explanation or particle to explain this.

- neutrino masses. The Standard Model predicts neutrinos to be massless, the observed phenomenon of neutrino oscillations however has proven otherwise.

- matter/antimatter asymmetry. The universe is made predominantly out of matter, the Standard Model however does not provide an explanation to this asymmetry.

Secondly, some theoretical problems have occurred. The Standard Model still contains 19 “free parameters”. Their values are known from experiments but their origin cannot be theorized.
1.1. THEORETICAL BACKGROUND

Other problems are the so-called hierarchy problem and strong CP problem. The two main extensions, called “beyond the Standard Model” theories, are the Grand Unified Theories (GUT) and Supersymmetry. The GUTs predict a unification of the electromagnetic, strong and weak force at high energies, energies close to the so-called GUT scale (approximately $10^{16}$ GeV). The difficulty is that at such large energies, new physics are expected. The current technology however does not yet allow to explore these experimentally. The second GUT is called Supersymmetry and adds an additional class of symmetry to the Standard Model. This symmetry is assumed to exchange fermions with bosons. If this were true, each particle would imply a new one, a sparticle (supersymmetric particle), doubling the amount of particles. The fact that sparticles have not been observed puts a lower limit on their mass. Sparticles would thus have to be much heavier than the known particles, with a production threshold far beyond the one of existing colliders.

1.1.3 Neutrino physics

The neutrino is an electrically neutral, weakly interacting, elementary subatomic particle with half-integer spin, coming in three flavours: the electron neutrino, the muon neutrino and the tau neutrino. Each neutrino has an antiparticle, called an antineutrino, which is also electrically neutral and has half-integer spin. It is not yet known whether the neutrino and the antineutrino are really distinct particles or rather different states of the same particle. Neutrinos are created in radioactive decay, as a product of nuclear reactions (such as in the sun and in nuclear reactors) and when cosmic rays hit the atmosphere. As mentioned, neutrinos where first theorized by Pauli in 1930 [33] to explain energy conservation in beta decay. This decay also lead to the first experimental observation of the neutrino in the Cowan-Reines neutrino experiment [34]. Antineutrinos, created through beta decay in a nuclear reactor, react with protons to form a neutron and a positron

$$\nu_e + p^+ \rightarrow n^0 + e^+ \quad (1.1)$$

Afterwards the neutron gets captured in a nucleus and the positron annihilates with an electron, leaving a unique signature of three gamma rays.

Neutrino oscillation

The nuclear fusion powering the Sun generates neutrinos, a part of which is sent in the direction of the earth. As a result each second about 65 billion ($65 \times 10^9$) solar neutrinos pass through each square centimetre of the sun-facing side of the earth, this is predicted by the Standard Solar Model. In the late 1960s, Raymond Davis and John Bahcall started the Homestake experiment, aiming at collecting and counting the amount of solar neutrinos. Surprisingly they only measured one third of the expected flux. This discrepancy was called the “solar neutrino problem”. Later a similar deficit was discovered in atmospheric, reactor and beam neutrino fluxes. The answer came in 1962 with the idea of neutrino oscillation, put forward by Maki, Nakagawa and Sakata [35], the concept however was first formulated in 1957 by Bruno Pontecorvo [36]. The Standard Model predicts neutrinos to be massless, their oscillation however proves otherwise. It is based on the neutrinos having three flavour and three mass eigenstates. Each flavour eigenstate, which interacts with the corresponding charged lepton, is a different superposition of the three mass eigenstates. Upon propagation through space, the quantum phases of the different mass eigenstates advance at different rates due to the difference in mass. This results in a changing mixture of mass eigenstates upon propagation, linked to a changing mixture of flavour eigenstates. A particle born as an electron neutrino can then change into a muon or tau neutrino after some distance. These oscillations however only depend on the square of the mass difference between the three types, not on their sign. This is the root of the mass
hierarchy problem, stating that for the time being it is impossible to deduce the exact mass difference hence the ordering of the neutrino masses.

Neutrino and antineutrino

Whether neutrinos and antineutrinos are each others antiparticle or they are actually the same particle is still unanswered. What is known is that they have a different helicity\(^2\). If this is a just a different helicity state of the same particle, the neutrino is a Majorana fermion. In the other case, if they are different particles with the same mass, neutrinos are Dirac fermions. Majorana particles were first theorized by Ettore Majorana in 1937 [37]. It is a consequence of the suggestion that neutral spin-\(1/2\) particles can be described by a real wave equation. Since the wave function of an antiparticle is the complex conjugate of the main particle wave function, this implies that both particles are the same. For now, no particles are known to be Majorana fermions but the neutrino is still under debate.

One way of finding the answer lies in the phenomenon of neutrinoless double beta decay. If this were to observed, it would directly prove the Majorana nature of the neutrino. Normal double beta decay is the simultaneous occurrence of two beta minus (\(\beta^-\)) decays, converting two neutrons from the nucleus into two protons with emission of two electrons and two electron antineutrinos. For this decay to be allowed, the final nucleus (with atomic number plus 2) must have a larger binding energy than both the initial nucleus and the intermediate nucleus (with atomic number plus 1). There are only 35 naturally occurring isotopes that are capable of undergoing double beta decay. If the neutrino is a Majorana particle and at least one type of neutrino has non-zero mass, neutrinoless double beta decay is possible. In essence, what happens is that the two neutrinos annihilate each other. Many experiments have been performed without finding uncontroversial positive evidence.

A second approach is the search for the production of same sign charged lepton pairs at hadron colliders. This is the high energy analogue of the neutrinoless beta decay process. It is being searched for by both ATLAS and CMS experiments at the Large Hadron Collider.

Neutrino astronomy

Due to their weak interactions, neutrinos can penetrate light years of matter and merely interact. This way they form unique messengers providing information that is otherwise inaccessible. All known neutrinos come from one of the following sources:

- artificial. Beta decay in nuclear reactors is the major source of human-generated neutrinos. Other artificial sources are certain particle accelerators and nuclear bombs.

- geological. Natural background radiation contains neutrinos. These are again the products of beta decay of certain isotopes.

- atmospheric. As cosmic rays interact with the Earth’s atmosphere, cosmic air showers are created. These consist of a large number of hadrons, mostly pions, which then again either decay or interact with atmospheric nuclei. The charged pions decay into muons and muon neutrinos.

- solar. The Sun gets its energy from nuclear fusion reactions, namely the proton-proton chain and the CNO-cycle. Most neutrinos are the product of the former reaction.

- supernovae. A supernova denotes the collapse of a massive star. A huge amount of gravitational energy is released of which neutrinos carry away the most. On the one hand there is the huge increase of matter density at the core, pushing protons and electrons to combine into neutrons and electron neutrinos. On the other hand there

\(^2\)Helicity is the projection of the spin \(\vec{s}\) on the direction of momentum \(\vec{p}\).
is the dissipation of the thermal energy ($10^{11}$ Kelvin), resulting in the formation of neutrino-antineutrino pairs.

- big bang. Just as the cosmic microwave background is left over from the big bang, a background of low energy neutrinos is left over and present in the Universe.

Besides the neutrino sources mentioned above, some more sources have been theorized but not yet observed:

- WIMP annihilations in the sun. WIMPs are weakly interacting massive particles. They are a candidate for dark matter, resembling neutrinos except for their larger mass. WIMPs can be captured gravitationally by the sun, upon which they accumulate and annihilate, forming high-energy neutrinos.

- supernova remnants (SNR). A supernova leaves a turbulent gaseous environment behind, called a supernova remnant. The mechanism of shock wave acceleration in these remnants is suspected to be the origin of cosmic rays.

- other extrasolar sources. Mainly active galactic nuclei (AGN) and gamma-ray bursts (GRB). The former are located at the centre of a galaxy, creating cosmic rays through mass accretion by a supermassive black hole. The latter comprises a large class of events upon which a flash of gamma rays is emitted, associated with high energy explosions in distant galaxies. Its signature is believed to be the gamma ray flash, preceded by a flux of neutrinos.

![Figure 1.5: Neutrino spectrum][38]

The expected fluxes and energy levels of the different neutrinos sources are shown in figure 1.5. The last five sources mentioned above form the basis of a new hatch in astronomy and astrophysics. The 20th century has allowed to stretch observational astronomy from the optical window to the whole electromagnetic spectrum. Also cosmic rays have proven to be adequate information carriers to study the (early) Universe. The problem with aforementioned methods
is twofold. As most of the interesting physics happens at the core region of stellar structures (stars, supernovae, Active Galactic Nuclei, ...), information carriers first have to move through the surrounding region which is possibly of high density. Their interaction with this region distorts both their energetic and spatial spectrum. Secondly the information carriers have to propagate through light years of interstellar space, leading again to interaction and distortion of the information they carry. Thanks to their weak interaction, neutrinos overcome these issues.

Neutrino astronomy brings information about the core regions of stellar bodies. Due to the absence of electric charge and the low probability of interaction with matter, neutrino fluxes arrive at the Earth nearly intact. This means that their energy loss is negligible as is their deviation of the initial direction. The downside is that, evidently due to their lack of interaction, they are hard to detect. Huge detectors, so called neutrino telescopes, are needed. As mentioned, the Cowan-Reines neutrino experiment lead to the detection of the first neutrinos, coming from a nuclear reactor. 12 years later the Homestake experiment lead to the detection of the first cosmic neutrinos, namely solar neutrinos.

1.2 Experimental aspects

As neutrinos interact in so little ways, ingenuity is required if one wants to detect them. A multitude of approaches has been developed and tried out, leading to several projects and operations.

1.2.1 Neutrino detection techniques

Neutrino interactions

Due to a lack of electric and colour charge, neutrinos are not affected by the strong and electromagnetic force. As gravitation is negligible on the subatomic scale, the only remaining force is the weak force. Its interactions can be divided in neutral current and charged current interactions. Neutral current interactions are mediated by a neutral vector boson, the Z boson. The following equations summarize the neutral current interactions of the neutrino

\[ \nu_l + N \rightarrow \nu_l + X \] \hspace{1cm} (1.2)
\[ \bar{\nu}_l + N \rightarrow \bar{\nu}_l + X \] \hspace{1cm} (1.3)
\[ \nu_l + e^- \rightarrow \nu_l + e^- \] \hspace{1cm} (1.4)

with \( N \) a target nucleon and \( X \) a hadronic cascade. \( \nu_l \) represents a neutrino of any of the three flavours. The last reaction represents an elastic scattering reaction with an electron, as this is the only lepton found in matter. Charged current interactions take place upon the exchange of a W boson, either positively or negatively charged. The exchange turns a neutrino in its corresponding charged lepton and transfers part of the kinetic energy to the nucleon, triggering again a hadronic cascade. The following two equations summarize the charged current interactions of a neutrino

\[ \nu_l + N \rightarrow l^- + X \] \hspace{1cm} (1.5)
\[ \bar{\nu}_l + N \rightarrow l^+ + X \] \hspace{1cm} (1.6)

Knowledge of these reaction channels allows different approaches towards the detection of neutrinos. The already mentioned Cowan-Reines experiment makes use of the inverse beta decay, a charged current interaction

\[ \bar{\nu}_e + p \rightarrow n + e^+ \] \hspace{1cm} (1.7)
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Neutrinos coming from a nuclear reactor interacted with protons in two tanks of water, creating neutrons and positrons. The first sign of the reaction is a pair of gamma rays when the positron annihilates with an electron. These gamma rays are detected by tanks filled with a liquid scintillator, surrounding the water tanks. The second sign is based on detection of the neutron. By placing cadmium chloride in the tank, a gamma ray is emitted through the following reaction\(^3\)

\[ n + ^{108}\text{Cd} \rightarrow ^{109\text{m}}\text{Cd} \rightarrow ^{109}\text{Cd} + \gamma \]  

(1.8)

The setup was made in such a way that the gamma ray from the cadmium would be detected 5 microseconds after the gamma rays from the positron, if an antineutrino was truly detected. A more recent and larger detector is the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), built near Toyama, Japan. It uses a similar technique to investigate neutrino oscillations, using neutrinos coming from over 50 nuclear power plants. Large detectors are preferred, compensating for the low neutrino interaction probability.

Cherenkov effect

An alternative to the above discussed techniques is brought up using the Cherenkov effect. This effect refers to the emission of electromagnetic radiation by secondary charged particles. Figure 1.6 shows Cherenkov radiation emitted around a reactor.

The Cherenkov effect is named after the Soviet scientist Pavel Alekseyevich Cherenkov, who first observed the effect in 1934 [39]. As a consequence of the effect, electromagnetic radiation named Cherenkov radiation is emitted when a charged particle traverses a dielectric medium\(^4\) with a velocity greater than the speed of light in that medium. The phenomenon is similar to the sonic boom, occurring when an object moves faster than the speed of sound. The phase velocity\(^5\) of light in a medium is defined by \(v_{em} = c/n\), with \(n\) the refractive index of the medium. The condition for Cherenkov radiation to occur is that

\[ v_{em} = c/n < u < c \]  

(1.9)

with \(u\) the charged particle velocity. When a charged particle moves through a dielectric medium it loses energy by polarizing the molecules surrounding the track. This way electric dipoles are generated along the particle trajectory. Relaxation of these molecules produces dipole radiation. When \(u < c/n\), the disturbance elastically relaxates to its (unpolarized) ground state, as shown on the left side of figure 1.7. The right side of the figure shows the case of \(u > c/n\). The radiation interferes constructively (as a consequence of the limited response speed of the medium) and a light cone is formed. Figure 1.8 shows the particle, with \(\beta = v/c\), \(\theta\) the half opening angle of the cone and \(c/n = v_{em}\) the speed of the emitted light waves (equal to the speed of light in the medium). As mentioned, this is analogous to a sonic boom. When an object travels faster than the speed of sound, the sound waves generated by the body travel slower than the body, preventing them from staying in front of the body. This results in a shock front.

The opening angle of the Cherenkov cone can be estimated using figure 1.8. At a time \(t = 0\), the charged particle enters the figure, producing the aforementioned light wave. After a time \(t \neq 0\), the particle has travelled a distance \(D = ut = \beta ct\) whereas the shockwave has only travelled a distance \(vt = \frac{\xi}{n} t < D\) (the particle travels faster than the local speed of light).

\(^3\)The intermediate cadmium isotope is a so-called meta-state or nuclear isomer. It denotes a meta-stable atomic nucleus caused by the excitation of one of its nucleons.

\(^4\)A dielectric medium denotes an electrically insulating material that can be polarized by applying an external electric field.

\(^5\)The velocity of a wave can be defined in different ways. The phase velocity denotes the velocity at which the phase of the wave propagates. It is different from the group velocity, which represents the wave modulation (in communication technology this part contains the information).
This leads to the half opening angle $\theta$ being

$$\cos \theta = \frac{1}{n\beta} \quad (1.10)$$

The spectrum of the Cherenkov radiation is given by the Frank-Tamm formula, named after the Russian physicists Ilya Frank and Igor Tamm. It is a continuous spectrum, unlike emission spectra. The relative intensity of one frequency is approximately proportional to that frequency. As a consequence, visible Cherenkov radiation is observed to be brilliant blue, as can be clearly seen in figure 1.6. A formulation of the Frank-Tamm spectrum is given by the following equation

$$\frac{d^2 N}{dx d\lambda} = \frac{4\pi^2 z^2 e^2}{hc\lambda^2} \left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi z^2}{\lambda^2} \frac{e^2}{\alpha} \sin^2 \theta \quad (1.11)$$

giving the number of photons $N$ per unit of length $dx$ and wavelength $d\lambda$. $ze$ is the particle charge, $n$ the refractive index of the medium and $\beta$ the particle velocity divided by the speed of light $c$ (in vacuum). For detection purposes roughly only the optical region is relevant, elsewhere the radiation absorption is too high or the refractive index becomes less than one. A Cherenkov detector is based on the unique properties of Cherenkov light. In different setups it makes use of the speed threshold, the speed-dependent output and the velocity dependent direction of the radiation. The designs can be divided into two classes, namely the Cherenkov threshold counters and Cherenkov imaging counters. In both cases the detection of the Cherenkov light is performed by photomultiplier tubes (PMTs). PMTs capture the radiation and convert it proportionally to an electric signal, allowing electronic readout. Cherenkov threshold counters are based on the Cherenkov radiation threshold $c/n < u < c$. 
This imposes a momentum threshold \( p_t \) on passing particles, given by the following equation

\[
p_t = m\gamma \beta c = \frac{mc}{\sqrt{n^2 - 1}} \tag{1.12}
\]

The threshold scales directly with the mass. For a beam consisting of one particle type, detection of the Cherenkov light allows discrimination of the particle energy. Besides that, for a charged beam energy above the threshold this technique allows fast counting of its particles, thanks to the small decay time of the dipoles.

The second class, Cherenkov imaging counters, uses information comprised in the Cherenkov cone. Its direction and opening angle contain information about the particle speed and direction. The first type, using only the light direction, is called a differential Cherenkov counter. The second type is called a ring imaging Cherenkov counter (RICH). Measurement of the Cherenkov cone opening angle allows identification of the traversing particle. The last type, named detector for internally reflected light, captures the Cherenkov light by total internal reflection and guides it to a PMT readout. Information about the initial cone is preserved as total internal reflection retains the initial angle of the light waves.

**Neutrino telescopes**

Neutrino telescopes usually are large volumes of water or ice. As traversing neutrinos are neutral particles, they do not generate electric dipoles and no Cherenkov radiation is produced. However, when they interact in the volume via charged currents, charged leptons are created. These leave a clear Cherenkov light signature. As the flavour of the created lepton and the incoming neutrino are the same, identification of the lepton flavour leads to the neutrino flavour. Each of the three leptons leaves a unique signature, allowing flavour identification:

- an **electron** produces a local signal. The initial interaction of the electron neutrino produces a hadronic shower and an electron, each of which produce Cherenkov radiation. The electron quickly loses its energy to Bremsstrahlung, creating photons which then again form electron-positron pairs. Because of the low interaction length of hadrons and electrons, both signals stay local.

- a **muon** leaves a long straight trace in the detector. Its Bremsstrahlung losses are much smaller due to its larger mass, the dominant energy loss is due to ionization of the water or ice. The long lifetime of a muon (\( \sim 2.2 \mu s \)) allows it to travel long distances in the telescope before disappearing into one of its decay channels. When the muon is generated, its direction will be close to the direction of the incoming neutrino. As the muon barely deviates from its path (scattering is negligible) its track forms a good indication of the initial neutrino direction.

- a **tau** lepton is associated with a so-called double-bang signature. The first bang corresponds to the hadronic shower, product of the charged current interaction. The second bang is a consequence of the short lifetime of the tau (\( \sim 0.29 \) ps). It will decay into a muon, an electron or hadronically. In the latter two cases a second, contained shower is observed.

The three signatures are represented in figure 1.9.

In Japan, the most important neutrino telescope based on the Cherenkov effect is the Super-Kamiokande (figure 1.10, left), operating since 1996. It is a water-filled detector, using 50000 tons of water surrounded by 11000 photomultiplier tubes, one kilometre underground. The Sudbury Neutrino Observatory (SNO, figure 1.10, right) is based in Ontario, Canada, operating from 1999 to 2006. It was situated two kilometres underground, using 1000 tons of water. Other neutrino telescopes that are based on the Cherenkov effect are ANTARES (Astronomy
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1.2.2 The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a neutrino telescope based at the Amundsen-Scott South Pole Station, Antarctica. The project is developed and supervised by the University of Wisconsin-Madison but funded by and in collaboration with numerous other universities and research institutions. Construction began in 2005 and finished in 2010.

Built inside the South Pole ice cap, IceCube uses approximately one cubic kilometre of clear ice as detection medium, making IceCube the largest neutrino telescope in the world. The Cherenkov light is detected by Digital Optical Modules (DOMs). These are, sixty at a time, deployed on long strings going down the ice, covering depths from 1450 m to 2450 m deep.
Figure 1.11 shows the different parts of the detector. The first part consists of the in-ice components IceCube and DeepCore, the latter being a more densely instrumented region allowing to detect lower energy neutrinos. The second part, the IceTop array, is a series of Cherenkov detectors placed on the surface aiming at the detection of cosmic ray showers and serving as a veto signal for IceCube. The real detection of the Cherenkov light and the following data acquisition is performed by the aforementioned DOMs, extensively explained in section 1.2.3. The information acquired by a DOM consists roughly of the intensity and the timing of the detected Cherenkov light. Together with the DOM position this leads to information about tracks and interactions of the traversing particles.

The main goal of IceCube is performing neutrino astronomy, allowing the detection of astrophysical neutrinos with energies from approximately 10 GeV to as much as a few PeV ($10^{15}$ eV). IceCube is the first neutrino telescope capable of detecting such high energy neutrinos. Furthermore it studies cosmic ray sources, searches for dark matter and digs deeper into the neutrino properties.

![Figure 1.11: Figure of the IceCube array [38].](image)

**IceTop**

The IceTop array is situated on the surface, above IceCube. This way most of the down going neutrinos have to pass through the array before reaching IceCube, allowing to perform preliminary measurements or selections. Cosmic ray showers are also detected. As these can possibly contain a large amount of muons, IceTop can discriminate the muons detected by IceCube as originating from cosmic neutrinos or from cosmic showers.

81 stations are placed above the 81 IceCube strings, each station consisting of 2 tanks next to each other. These tanks contain an ice layer in which two DOMs are embedded. The PMTs inside the two DOMs are operated at different gains, allowing them to cover different energy regions.
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Figure 1.12: Top view of the IceCube array [38].

IceCube and DeepCore

The in-ice part comprises 5160 DOMs, distributed over 86 strings, covering the depth between 1450 m and 2450 m. This is where the ice is clear and its absorption of Cherenkov light is limited. Furthermore, the 1450 m of ice above the detector serves as a filter for cosmic ray showers. The strings are arranged in a triangular grid over a square kilometre, spaced 125 m apart. At the centre, strings are placed more densely, spaced only 17 m apart. This section is called DeepCore, it allows a lowering of the neutrino energy threshold from $\sim 100$ GeV to $\sim 10$ GeV. This is caused by the fact that the lower the neutrino energy is, the lower the charged lepton energy will be and as a consequence its track length and the amount of Cherenkov light produced will be smaller.

Goals

The goals of the IceCube Neutrino Observatory are manifold. Most notably it investigates the origin of the highest energy cosmic rays. These are measured to be too energetic to originate in our galaxy, thus suggesting their source to be extra-galactic. Furthermore the creation of such high energy cosmic rays is expected to be accompanied by the production of high energy neutrinos, which can reach the earth nearly without being deflected. IceCube is designed to detect these extra-galactic neutrinos, reading almost directly the information they carry about extra-galactic events. The detected amount of neutrinos is low, negligible even in comparison to photon rates in optical astronomy. The ones that are detected however are of extremely high resolution. Several years of operation will allow to form a precise map of the neutrino
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fluxes in the northern hemisphere\textsuperscript{6}, similar to the cosmic microwave background map.
A second phenomenon IceCube looks for are neutrino fluxes in coincidence with Gamma-ray Bursts (GRBs). GRBs have long been suggested to have the same origin as the above-mentioned extragalactic cosmic-ray sources \cite{46}. This would be the case if simultaneously and with an equal efficiency protons and electrons were accelerated. The electrons produce the GRBs whereas the protons form the high-energy cosmic rays observed at the Earth. It is however \(p\gamma\) (proton-photon) interactions in the primary fireball that are suggested to produce muons, pions, kaons and neutrons, subsequently decaying in high-energy neutrinos. Data from IceCube is being used in conjunction with gamma-ray satellites to look for the resulting coincidental gamma and neutrino flux.

In section 1.1.3 WIMP annihilations in the sun and supernovae were named as hypothetical neutrino sources. IceCube is looking into detecting such neutrinos and thus confirming these sources. As for supernovae, if they take place outside our galaxy the resulting neutrino flux will be too low for IceCube to resolve them from background noise. However, neutrinos from local supernovae, taking place within our galaxy, should be detected. Other goals brought forward are constraining the neutrino oscillation parameters and possibly a future search for sterile neutrinos\textsuperscript{7}.

PINGU

PINGU stands for Precision IceCube Next Generation Upgrade. It is a proposed extension of IceCube aimed at increasing the detector sensitivity in the low GeV region. This is performed by further increasing the string density in the IceCube core region. The primary goal is measuring the currently unknown mass ordering of the three neutrino types. Furthermore it would look for low-mass dark matter particles. The Wavelength-shifting Optical Modules investigated in this thesis might be deployed by PINGU.

1.2.3 Detection of Cherenkov radiation: optical modules

IceCube is based on the detection of Cherenkov light, allowing to reconstruct and identify traversing particles. At the moment so-called DOMs are used, employing a large photocathode area to capture the photons. One way of raising the IceCube detection efficiency is maximizing this active area. However, as the following section explains, this cannot go uncompromised. Therefore an alternative is suggested, namely substituting the active photocathode area with a passive wavelength-shifter surface. Such a device is called a Wavelength-shifting Optical Module, further explained in section 1.2.3.

Digital Optical Module

Figure 1.13 shows the main parts of an IceCube DOM \cite{47}. All components are kept inside a spherical pressure housing made out of glass. The capture of the Cherenkov photons and the subsequent conversion into a detectable electric signal is performed by a 25 cm diameter photomultiplier tube (PMT). Between the PMT cathode and the glass housing an optical gel is applied, providing optical coupling\textsuperscript{8} and mechanical support. A mu-metal wire cage is placed around the PMT to shield it magnetically. Also shown on figure 1.13 are 4 electronic

\textsuperscript{6}IceCube is more sensitive to neutrinos coming from the northern hemisphere than from the southern hemisphere. This is a consequence of the earth operating as a filter for cosmic ray background muons, only allowing the passage of neutrinos.

\textsuperscript{7}As opposed to active (left-handed) neutrinos, sterile neutrinos are right-handed, making them hypothetical, nearly non-interacting particles which can travel faster than the speed of light. They are a candidate for Dark Matter and could explain the mass of neutrinos.

\textsuperscript{8}Optical coupling denotes the use of an intermediate material mediating the transfer of photons between two materials with a different refractive index. A mismatch easily leads to reflection rather than absorption at the surface.
boards (PCBs). The upper one is a high-voltage divider circuit, applying the voltage to the PMT anode and dynodes. Next is an LED flasher board containing six pairs of LEDs. The third board is the DOM mainboard responsible for the data acquisition and the fourth board is a 75 ns delay line. Penetrating the housing is a shielded cable supplying the power and allowing communication via a copper wire.

![Figure 1.13: Figure showing the main parts of a Digital Optical Module [38].](image)

The LED flasher board is used for calibration purposes, to determine the optical properties of the ice and to measure the precision of timing. As they produce extremely bright flashes ($\sim 6 \times 10^9$ photons/LED/pulse), they can be seen by other DOMs several hundred meters away. Another advantage of the pulses’ high brightness is that occurrence of single photon statistics and scattering in the ice contribute only little to the spread of the pulse.

Figure 1.14 shows the reconstruction of passing leptons, based on the signal picked up by the DOMs. Each track can trigger multiple DOMs, the amount of DOMs triggered is called the hit multiplicity. The higher the hit multiplicity, the higher the resolution of the track reconstruction. With an event hit multiplicity of 8 or more, the incoming muon angle (zenith) can be reconstructed with an rms resolution of 9.7°. This resolution improves rapidly with a higher multiplicity.

![Figure 1.14: Reconstruction of passing leptons by the IceCube DOMs, the coloring represents the time differences. (a) Electron signature, (b) muon signature, (c) tau signature [38].](image)

The capture of Cherenkov light by the DOMs is crucial for the working of IceCube. As its resolution is determined by the hit multiplicity, the capture efficiency directly imposes an energy threshold on the particle detection. The light yield of a particle is directly related to
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its energy. If its energy is too low, a DOM will not be able to resolve the signal from the PMT
noise and IceCube will not be able to detect the particle. A better detector resolution can
be accomplished by increasing the supply voltage or enlarging the photocathode area, which
is likely to increase the hit multiplicity. Note that only the first possibility is applicable in
the case of IceCube, the other possibility would require new optical modules. Raising the
supply voltage however can not be applied unambiguously. A larger supply voltage means a
higher gain, thus increasing the sensitivity. The downside is that this is directly linked to a
raise in the PMT noise and a loss of PMT resolution, as the huge amplification stage will no
longer allow identification of single photoelectron peaks. Enlarging the photocathode area is
the second approach towards a better resolution. This will also induce an increase in the PMT
noise, as the thermoelectric noise is proportional to the cathode size. Moreover, increasing
the current photosensitive area of IceCube by a factor of a few would be a serious financial
challenge.

Wavelength-shifting Optical Module

An alternative to the DOMs is provided by making use of wavelength-shifting technology.
Wavelength-shifter bars (WLSs) are passive components able of absorbing light and reemitting
it at a longer wavelength. This allows to limit self-absorption and a better matching of the
collected light to the PMT sensitivity. The principle is further explained in section 2.2.1.
WOMs form an alternative to the above-mentioned DOMs by using a wavelength-shifter as
sensitive surface, collecting Cherenkov light. Most wavelength-shifters are manufactured by
dissolving wavelength-shifting molecules in a liquid or plastic, providing much freedom in the
design of the light-collecting surface. Figure 1.15 shows a design suggested by Lukas Schulte
[48]. The design suggests the use of a WLS paint on a circular tube, forming the WOM’s
sensitive surface. The Cherenkov light, mainly in the UV region, is captured and re-emitted
isotropically, allowing its capture and propagation inside the WLS material. At the top and
bottom of the tube this light is lead to PMTs using light guides. Note that these PMTs can
be a lot smaller than the DOM PMTs as the light is already bundled into the light guides.
Using the appropriate WLS, the light entering the PMT has been shifted from UV to optical
blue, better suited to the PMT efficiency. The idea of using a passive component to collect
light lowers the noise up to two orders of magnitude [48]. The whole assembly is housed inside
a pressure vessel, protecting it from its environment.

A qualitative comparison can be made between the DOM and WOM design. Firstly their
difference in geometry leads to a different angular acceptance $\epsilon_\Omega$. This denotes the probability
that a photon enters the module at a place where it can be absorbed, in function of its
incidence angle (w.r.t. the vertical axis). The maximum probability occurs at perpendicular
incidence to the sensitive area and is dependent on the transition probabilities through the
housing material. Gauging on this maximum, the relative angular acceptance of the DOM
and WOM can be calculated on geometric basis. The result is shown on the left of figure
1.16. Integrated over all angles this gives a mean angular acceptance of $\bar{\epsilon}_\Omega$(DOM) = 34.1%
and $\bar{\epsilon}_\Omega$(WOM) = 57.5%. The full module efficiencies, denoting the mean probability of a
Cherenkov photon being captured and conversed by the PMT in function of its wavelength,
are shown on the right of figure 1.16. These are however very dependent on the specific
materials and PMTs used. The figure shows the case for the design of Lukas Schulte, compared
to a veritable DOM. On first sight the WOM efficiency is the poorest. However taking into
account the Cherenkov distribution, showing a $1/\lambda^2$ dependency, the performance of the WOM
increases significantly in comparison to the DOM.

As mentioned, thanks to the passive light collection, the noise rate of a WOM lies an order of
magnitude lower than the DOM noise rate. Whereas the rate of noise pulses in a DOM can be
more than 500 Hz, in the WOM case a rate of the order of 10 Hz seems possible. A last point
to be made is the flexibility in design of a module based on wavelength-shifting technology.
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Figure 1.15: Proposed design of a WOM [48].

Figure 1.16: Left: comparison of the relative angular acceptance of a DOM and a WOM, right: comparison of the full module efficiency of a DOM and a WOM [48].

Its size can be easily increased without problematically increasing the noise rate, in the case of a DOM will not only the noise rate but also the cost go up very easily.
Chapter 2

WOM setup

The experimental setup uses a water tank as active volume, mimicking the conditions of the IceCube Neutrino Observatory. Traversing particles produce the sought-after Cherenkov light in water whereas IceCube uses Antarctic ice as its active volume. However, what the Cherenkov effect concerns, water and ice act similar. Figure 2.1 shows a picture of the setup. The two main parts of the detector are the water tank, housing a wavelength-shifter bar, and the trigger, consisting of a scintillator array above and below the tank. On the right side the data acquisition modules can be seen, initialized and read out both manually and by the PC. The setup was built in 2012 and was used for a similar purpose by Simon De Rijck [49].

Figure 2.1: Photo of the setup [49].

2.1 Muon trigger

The trigger is designed to detect atmospheric muons passing through the array. Its response is used both as a signal to start measuring the WLS PMTs and to help discriminate between
events during the data acquisition. The use of two separate arrays surrounding the tank shows some advantages. By performing a coincidence check between both arrays a lowering of the noise signals can be accomplished. Furthermore this check allows verification of whether a particle traversed the entire tank or left sideways or was absorbed in the tank. The triggering mechanism is based on a mechanism called scintillation counting.

2.1.1 Scintillation counting

Scintillation is basically a quantum-mechanical process, closely related to luminescence or the emission of light not resulting from heat. It is an inherent property of organic molecules, whereas only some inorganic molecules possess it. In the case of organic molecules, scintillation is caused by the excitation and subsequent de-excitation of molecular energy levels. Upon incidence, a particle can excite the molecule, inducing a transition of a free valence electron to a higher energy state. The electron will then relax into an intermediate state, emitting heat instead of light, before performing its main relaxation back into the stable ground state. The left side of figure 2.2 shows a scheme of both fluorescence and phosphorescence, using electron energy states. Scintillation is a fluorescent process, doing both relaxations almost immediately, thus emitting its light instantaneously. Phosphorescence denotes the process where an extra intermediate state is visited by the electron. This extra state, a triplet state, has a longer decay time, delaying the relaxation and light pulse. The radiated energy of the de-excitation will always be lower than the absorbed energy. This shift is called the Stokes shift. Thanks to this shift the emitted radiation energy is too low to create new excitations. The radiation will thus propagate nearly unhindered through the material, allowing for efficient readout. Organic scintillators are often dissolved in an organic solvent, forming a liquid or plastic scintillator. In that case the main energy absorption is performed by the solvent, which is only secondly passed onto the scintillating solute.

In the case of inorganic molecules forming a crystal, scintillation is based on energy bands. These are a consequence of interactions with the crystal as a whole, rather than on a molecular level. An incoming particle can excite an electron to either the conduction band or the exciton band, creating an electron-hole pair. If the crystal contains the appropriate impurities, intermediate states are created between the valence and conduction band called activator states. When the incoming particle created an exciton, being an electron-hole pair that is still bound by the Coulomb force, this exciton can as a whole be captured by the impurity. The following de-excitation of this impurity state emits electromagnetic radiation, called scintillation light. The scintillation light is shifted to a lower energy, again referred by to as the Stokes shift, preventing the crystal from reabsorbing the light. This mechanism is called the fast component of the scintillation process. If initially the electron is excited to the conduction band rather than the exciton band, the electron and hole become decoupled. They will successively be captured by the impurity centres, creating metastable states with a delayed relaxation. This mechanism denotes the slow component of scintillation.

Commercial scintillator bars are characterised using the following properties:

- light yield. This is a measure for the quantum efficiency of the scintillation process, namely the fraction of the absorbed energy converted into scintillation light. This should be as high as possible.

- absorption and emission spectrum. The absorption spectrum is characterised by the scintillator energy levels and should show as few overlap with the emission spectrum as possible. The absorption length is closely related to the absorption spectrum. This is a measure representing the length after which the probability of a passing photon not being absorbed in the medium has dropped to $1/e$.

\footnote{For the treatment of scintillation, an approach using molecular energy levels is preferred rather than atomic levels. This implies electrons associated with the whole molecule.}
2.1. MUON TRIGGER

- decay time. This is directly related to the stability of the intermediate excited levels. In order to have small dead-times, the scintillator decay time should be as low as possible. This way the signal of a passing particle can be processed fast, making room for new signals.

Concerning the setup, each trigger array consists of 8 horizontal scintillator bars, covering the entire trigger surface and overlapping the water tank. The scintillator bars are of the organic type IHEP_SC-201, dimensions 10 cm x 60 cm x 2 cm. According to the manufacturer, SRC IHEP, the bars have a light yield of 55% Anthracene\(^2\), a decay time of approximately 2.4 ns, an absorption length of 2 m and a maximum emission at a wavelength of 420 nm [50]. The scintillator bars have 4 grooves on their surface, holding optical fibres. As the scintillation light is emitted isotropically, these capture the light and help transport it to the sides of the scintillator bar, where it can be captured by PMTs. To further decrease light loss, the scintillator is wrapped in a reflective foil, limiting the losses at the surface. The capture of the scintillation light by the WLS and fibres is based on a principle called total internal reflection. Figure 2.3 shows a picture of the scintillator bars, separate and in the trigger array, and a drawing clearly indicating the optical fibre readout paths. The principle of using a scintillator in conjunction with a PMT is called scintillation counting.

Figure 2.4 shows a scheme of the final setup used. It shows the PMT charge read out by a CFD module. CFD stands for constant fraction discrimination. This is a technique specifically designed for pulse timing or the extraction of a trigger signal from pulses with varying width and height. Concerning the readout of the different PMTs, a first problem arising is that the response is a pulse with a certain rise time. When this time is longer than the temporal resolution aimed at with the trigger, the timing will be erroneous. The second problem occurring is that PMT responses can differ a lot in height. When using simple threshold triggering the trigger timing will be dependent on the pulse height, which is unwanted. This effect is called time walk. Constant fraction discrimination takes these effects into account, at least in the case of pulses with identical rise times and peak shapes, as is the case for the PMT response. The trigger signal is generated a fixed time after the leading pulse side has crossed a constant fraction of its maximum amplitude.

\(^2\)The light yield of a scintillator is often expressed as a percentage of the light yield of anthracene, which has the highest light output of all organic scintillators. It produces about 2 photons per 100 eV deposited.
Figure 2.3: (a) Picture of one of the scintillator array. The scintillator bars are covered with a copper foil to reduce light losses at the surface [49]. (b) Figure of a scintillator array, showing the optical fibres and PMT readout [49].

Two CFD modules are used to read out each scintillator bar individually, the modules used are of the type CAEN Mod. V812 16 Channel. These modules generate a logic pulse whenever an appropriate particle passes through the scintillator bar, creating a scintillation pulse.

Figure 2.4: Figure of the experimental setup, showing the tank, scintillation triggers and readout chain.

2.2 Cherenkov light detector

The production of Cherenkov light is performed in a tank containing 168 l distilled water, lowering the scattering of light. Its dimensions are 0.6 m x 0.8 m x 0.35 m. The sensitive surface, collecting the light, is formed by a wavelength-shifting bar.
2.2. CHERENKOV LIGHT DETECTOR

2.2.1 Sensitive surface: wavelength-shifting bar

A wavelength-shifting bar or simply wavelength-shifter (WLS) represents a plastic scintillator doped with wavelength-shifting molecules. The most important property of these molecules is their Stokes shift. This is a lot larger than the one from normal scintillators, minimizing the overlap between its emission and absorption spectrum (figure 2.5). Its self-absorption will thus be much lower, increasing its capture efficiency. In the case of scintillation counting, this property can be used to absorb Cherenkov light and subsequently shift it to a longer wavelength, better adjusted to the readout PMTs. The usage of a WLS to collect Cherenkov light provides some major advantages in comparison to the usage of a PMT photocathode. First of all it can be made both in a liquid and a plastic form, allowing much freedom in its geometry and size. When it captures light it will re-emit it isotropically, as is the case for scintillation. Upon placement in a medium with a lower refractive index, the principle of total internal reflection captures a large part of the scintillation light inside the WLS, forcing it to mainly propagate to the sides where it can be read out by a much smaller PMT cathode. The main idea is the separation of light-collection and light-conversion, in this case respectively by the WLS and the PMT. As mentioned in section 1.2.3, the photocathode surface of the PMT is limited due to noise and cost. This is not the case with a WLS. Another advantage is that a WLS can collect light from all directions, allowing sensitivity to the full $4\pi$ solid angle. A DOM is usually only sensitive to a $2\pi$ solid angle as a consequence of one side of the PMT being instrumented. One downside is that the capture efficiency of a WLS is a lot lower than the one of a PMT. This is caused by light propagation losses inside the WLS, mainly due to refraction losses at the surface.

The WLS used is of the type BC-482A with dimensions 10 cm x 0.5 cm x 80 cm, produced by Saint-Gobain Crystals. The decay time, as provided by the manufacturer, is 12 ns. The absorption and emission spectrum are shown in figure 2.5.

![Figure 2.5: Stokes shift of the WLS used [51].](image)

2.2.2 Active surface: WLS readout

The WLS is placed at one fifth of the tank height, allowing the biggest part of the water to be above the WLS. Part of the left and right sides are read out by two PMTs, penetrating the tank both left and right. They are 10-stage PMTs of the type XP1911/UV, manufactured by Photonis [52]. The WLS emission spectrum is shifted to a region with a lower PMT absorption probability, leading to many photons getting lost. As the PMT cathode diameter is only 15 mm whereas the WLS width is 10 cm, only part of the WLS side is read out (see figure 2.6). The remaining part of the PMT cathode is covered, allowing only photons from the WLS to reach the photocathode. To limit refraction losses at the WLS-PMT interface, an optical
coupling gel is applied.

Figure 2.6: Pictures of the WLS and PMT placement with (a) the PMTs uncovered and (b) the PMTs covered [49].

### 2.2.3 Signal processing and DAQ

The data acquisition chain is drawn in figure 2.4. The 16 signals from the scintillator PMTs are processed by two constant fraction discriminator units, generating logic pulses. Upon reception of a gate signal, the WLS PMTs are read out by a charge-to-digital converter module, converting the integrated PMT charge to a discrete amount of counts. The gate signal is generated by a logic pulse from either the upper or the lower scintillator. To afterwards check for every gate which scintillator PMTs were triggered, the CFD outputs are also sent to a time-to-digital converter unit. This unit records the amount and position of the triggers and their exact timing up to a precision of 100 ps. Both the QDC and TDC data is sent to a PC. Using ROOT, a data analysis framework developed by CERN, the data of every single event is written into data structures, allowing to capture as much information as possible and process it afterwards.

### 2.3 PMT calibration via different sources

The experimental setup contains two sets of photomultiplier tubes. The first set, consisting of 16 PMTs, is used to read out the scintillators of the two trigger planes. The second set, consisting of 2 PMTs, is used to read out the two sides of the wavelength shifter. Both sets serve different goals and are used under different circumstances, the main difference being the light intensity. As different PMTs have different response spectra, caused by construction imperfections etc., a calibration is necessary. This calibration is essential mainly for two reasons. The first one applies to the trigger PMTs. It has to be assured that different PMTs respond uniformly to the same input signal. This prevents for instance the trigger from being spatially biased, giving different efficiencies at different places in the trigger planes. Also towards the energy spectrum of incoming muons a uniform response is needed. The second reason applies to the WLS PMTs and concerns the interpretation of the exact PMT response. By performing an absolute calibration, as explained later, a good measure can be made of the exact amount of photoelectrons created. This is a measure for the amount of photons incident on the photocathode.
2.3.1 Trigger PMTs and scintillation light

The trigger mechanism only needs to know whether an event occurred and its timing, no information is needed about the precise PMT response (e.g. amount of photoelectrons created). The extraction of the trigger information is performed by the V812 CFD module, creating a signal pulse when the PMT output exceeds a certain threshold. As a consequence, no absolute calibration has to be performed. The calibration of the scintillation PMTs focuses on a uniform response concerning the incoming muon energy and location using only the trigger rates.

The 16 scintillation counting channels are calibrated to each other based on their trigger rate. It is assumed that the particle flux through all the bars is equal, thereby assuming a uniform particle flux and the fact that almost no particles are stopped by the upper array or tank. If this is the case, each scintillator should produce a similar light output spectrum, both in shape and in time, during longer measurements. By assuming each scintillator bar to give the same output, its output can be used as a gauge for a relative calibration. An equal CFD trigger rate for each scintillator PMT is aimed at, as this is the only output information that can be unambiguously measured. The rate to aim for is defined by some constraints.

- **The rate should be lower than the cosmic muon rate.** If this is not the case, the trigger is clearly generating pulses for unwanted particles. The cosmic muon rate at sea level is approximately 1 muon per cm$^2$ per minute [53]. Taking into account the size of the scintillator bars, the muon flux is approximately 600 muons per minute per bar or $r_{\mu,max} = 10$ Hz.

- **The rate should be considerably higher than the PMT noise rate.** A known issue with PMTs is the fact that they produce a fair amount of noise pulses. The rate of these pulses is easily measured by covering up the PMT cathode and measuring the trigger rate. Such a measurement showed that for voltages lower than 1500 V, the rate does not exceed 0.1 Hz.

Roughly sketched, each scintillation trigger has two parameters. The first one is the PMT voltage, the rate is expected to increase proportional to the voltage. The second parameter is the CFD threshold, the rate is expected to decrease proportional to this number. As only the rate needs to be calibrated, one of both parameters could be held fixed, allowing to take other factors into account. However, not all the PMTs have an individual power supply, forcing to use both parameters in order to tune the rates. The calibrated settings are shown in table 2.1. All the rates are between $r_{\mu} = 2.30$ Hz and $r_{\mu} = 3.52$ Hz. Figure 2.7 shows the rates of a $10^6$ events measurement, both for a full tank and an empty tank. The mean rate of the upper array for the full tank is $r_{\mu} = 2.99$ Hz and $r_{\mu} = 3.00$ Hz for the empty tank. The mean lower rates are $r_{\mu} = 2.75$ Hz for the empty tank and $r_{\mu} = 2.69$ Hz for the full tank. The minor decrease in the mean rate of the lower array after filling of the tank is presumably a consequence of particles being stopped by the water.

Although no further information is needed, some considerations are made concerning the scintillator PMT response. A back-of-the-envelope calculation of the expected scintillation light yield per muon is made using the scintillator characteristics [50]:

- type: IHEP,SC-201, manufacturer: SRC IHEP facilities
- light yield: 55% Anthracene or 1 photon/100 eV
- wavelength of maximum emission: 420 nm

Assuming a stopping power of 2 MeV/cm [54], a 1 GeV muon will deposit the following amount of energy:

$$E_{\text{dep}} = 2 \text{ MeV/cm} \times 2 \text{ cm} = 4 \text{ MeV},$$

(2.1)
using the scintillator thickness of 2 cm. This leads to an amount of $4 \times 10^4$ scintillation photons per event, with wavelength centered around 420 nm. As will be shown in the next section, this indicates an entirely different PMT regime than is the case for the WLS PMTs. The trigger PMTs capture bursts of photons rather than single photons. The PMT response is thus expected to form a broad Gaussian distribution with an power-law tail. This tail is a direct consequence of the muon high energy tail, as higher energy muons will create larger scintillation bursts. The left side of figure 2.8 shows a typical scintillation measurement of the QDC response of scintillator PMT 1. The charge measurement seems to indicate that the central value of the distribution is above the cut-off value (around 40 counts) introduced by the CFD threshold scan. This is essential in order to pick up most of the passing muons. The right side of figure 2.8 shows a measurement of scintillator PMT 8, suggesting a central value below the threshold. To check whether the central value of a scintillation charge distribution really falls above or below the threshold, a fitting is performed. The used function is a Crystal Ball function, named after the Crystal Ball Collaboration [55]. It consists of a Gaussian core and a power-law high-end tail. This fitting leads to a measure of the central value $Q_0$, around which the Gaussian peak is distributed. Figure 2.8 shows the fitting of a Crystal Ball function to the scintillator PMT responses. The fitting to the upper measurement shows a central value $Q_0 = 110$, above the threshold value. This was the case for most of the scintillators and was expected. The lower measurement however suggests a central value left of the cut-off value, indicating that the largest part of the scintillator bursts are not picked up. Lowering of the threshold value did not seem to improve this result. As the main focus was on calibrating the rates, no further attention was paid to this discrepancy.
2.3. PMT CALIBRATION VIA DIFFERENT SOURCES

<table>
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<tr>
<th>PMT</th>
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<th>CFD thr.</th>
<th>$r_\mu$ [Hz]</th>
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<td>30</td>
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<td>28</td>
<td>1405</td>
<td>24</td>
<td>2.76</td>
</tr>
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Table 2.1: Settings of the calibrated scintillator PMTs and CFD module. The rates shown are for the empty tank.

![Figure 2.8](image)

Figure 2.8: Fit results of two scintillator charge measurements to a Crystal Ball function. Left: QDC response of scintillator 1 showing the expected central value $Q_0$. Right: QDC response of scintillator 9 showing a central value below the threshold $Q_0$.

2.3.2 WLS PMTs and Cherenkov light

The two photomultiplier tubes positioned at the sides of the tank aim at reading out part of the WLS sides, capturing light that was absorbed and re-emitted by the WLS. When the trigger system generates a gate signal, caused by the crossing of a muon, the response of these PMTs is measured. This response no longer serves merely as a trigger, additional information
will be extracted from the response. As the goal is to obtain information about the WLS performance, it is necessary to extract information about the amount of photons caught by the PMTs. An absolute calibration allows to deduce this information from the PMT response. Based on the simulation only a couple of photons incident on the WLS PMTs are expected per event. This underlines the different regime under which the WLS PMTs are operated as opposed to the scintillator PMTs.

For the absolute calibration, a first approach was based on calibration using a known light source. Ideally this would be a single photon source, allowing to directly link the incoming photon energy to the combined PMT and QDC response. To accomplish this a laser diode (Roithner STAR405F5 [56]) was pulsed as short as 20 ns, after which its light output was filtered by a sequence of optical density filters. Using the following calculation the expected output could then be reduced to a single photon:

$$N_\gamma = \frac{P_{\text{laser}}[J] \times \Delta t_{\text{pulse}}[s]}{E_\gamma[J]} \times T \leq 1$$

(2.2)

for $\Delta t = 20$ ns, $P_{\text{laser}} = 5$ mW, $E_\gamma = 5 \times 10^{-19}$ J ($\lambda = 405$ nm) and $T = 10^{-8}$. What has to be taken into account however is the working principle of the laser. The laser does not emit single photons but on each pulse generates a coherent bunch. At the moment, in the light of quantum computing, research is being done towards the development of single photon lasers (e.g. [57]) but this is evidently well beyond the scope of this thesis. It is for that reason that a different approach was taken. Instead of using a well-known light source, a well-founded fitting function is proposed. Fitting of the PMT response to the laser output then leads to the sought-after PMT characteristics. This is a statistical approach but was to be expected as the different stages of the PMT all act in a statistical fashion. To theorize the general PMT response, the approach suggested in by E.H. Bellamy in [58] is followed.

General PMT response

The photomultiplier can be treated as consisting of two subsystems - the photodetector, converting photons into photoelectrons and the amplifier (dynode system), amplifying the photocharge into a measurable signal. To interpret PMT measurements, a model for the PMT response should be created containing the parameters that need to be calibrated. In case of a steady light source (or no source) the photodetector can be described by a Poisson distribution

$$P(n; \mu) = \frac{\mu^n e^{-\mu}}{n!}$$

(2.3)

where $P(n; \mu)$ is the probability that $n$ photoelectrons are collected by the first dynode when $\mu$ is the mean number of collected photoelectrons. $\mu$ is directly related to the intensity of the light source. If the amplification of the first dynode is large the amplifying system can be approximated by a Gaussian distribution

$$G_1(x) = \frac{1}{\sigma_1 \sqrt{2\pi}} \exp \left( -\frac{(x - Q_1)^2}{2\sigma_1^2} \right)$$

(2.4)

where $x$ is the charge at the cathode, $Q_1$ the average output charge for one photoelectron and $\sigma_1$ its standard deviation. In the case of $n$ photoelectrons, the distribution becomes the convolution of $n$ single photoelectron distributions:

$$G_n(x) = \frac{1}{\sigma_1 \sqrt{2n\pi}} \exp \left( -\frac{(x - nQ_1)^2}{2n\sigma_1^2} \right)$$

(2.5)

For $n \rightarrow 0$, $G_0(x) = \delta(x)$, assuring that when no photoelectron is created no charge is created. The response of an ideal PMT is a convolution of $P(n; \mu)$ and $G_n(x)$.
2.3. PMT CALIBRATION VIA DIFFERENT SOURCES

\[ S_{\text{ideal}}(x) = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma_1 \sqrt{2\pi n}} \exp \left( -\frac{(x-nQ_1)^2}{2n\sigma_1^2} \right) \] (2.6)

The three parameters for this response distribution are \( \{\mu, Q_1, \sigma_1\} \). In reality different background processes (noise) contribute to the signal, flattening out the discrete peaks of equation 2.6. These processes can be roughly divided into two groups

1. low charge processes - responsible for non-zero distribution when no photoelectron was captured (pedestal peak)
   \[ \rightarrow \text{gaussian distribution} \]

2. discrete processes - accompanying the measured signal (thermoemission amongst others)
   \[ \rightarrow \text{exponential distribution} \]

When no photoelectrons are emitted \((n = 0)\) the total signal is due to the background and is described by

\[ B(x) = \frac{(1-w)}{\sigma_0 \sqrt{2\pi}} \exp \left( -\frac{x^2}{2\sigma_0^2} \right) + w \theta(x) \alpha \exp (-\alpha x) \] (2.7)

with

- \(\sigma_0\) the standard deviation of the low charge background
- \(w\) the probability of a discrete background process accompanying a measurement
- \(\alpha\) the coefficient of the exponential decrease of discrete background processes
- \(\theta(x)\) the step function

For a non-zero amount of photoelectrons, both equation 2.6 and 2.7 contribute to the signal so the final PMT spectrum is the convolution of the ideal response (equation 2.6) and the background processes (equation 2.7), the details of which are discussed in appendix A. Additionally, when reading out the PMT with a QDC, a pedestal offset \(Q_0\) is read out. Its main cause is the QDC pedestal current. This is a bias current causing a constant shift of the input charge to a higher region, where the QDC has a linear behaviour. In the complete model there are seven free parameters describing the PMT response. These are

- \(\{Q_0, \sigma_0\}\): value and standard deviation of pedestal peak
- \(\{Q_1, \sigma_1\}\): value and standard deviation of single photoelectron peak
- \(\{w, \alpha\}\): describe background processes
- \(\mu\): the ratio of the amplitude of the photoelectron peaks over the pedestal peak, thus denoting the probability per event that a photoelectron will be created. This parameter is expected to be proportional to the intensity of the light source.

To show the effect of the background, two spectra are generated in figure 2.9, one without background \((w = 0)\) and one with background \((w = 0.5)\). The dotted peaks correspond to a discrete amount of photoelectrons generated, shown from zero to four photoelectrons. It is clear that the background processes add a tail to the expected gaussian distribution.
Figure 2.9: Simulated PMT response, parameters used: \( \{\mu, Q_0, \sigma_0, Q_1, \sigma_1, w, \alpha\} = \{1.75, 25, 0.35, 30, 12.0, w, 0.045\} \), 10^5 events simulated. Left: without background, right: with background.

**Fitting results**

All the following measurements were performed on the two WLS PMTs. The results presented are of WLS PMT 1, the results of WLS PMT 2 are shown in appendix B. Both the supply voltage of the laser \( V_L \) and the PMT \( V_{PMT} \) are varied. The incident light intensity is expected to size with the laser voltage. As one of the parameters, \( \mu \), represents the mean number of collected photoelectrons, a correct fitting should show a correlation between \( \mu \) and the laser voltage. The PMT supply voltage determines the gain, related to \( Q_1 - Q_0 \) - the amount of charge in QDC counts created by one photoelectron. Also here a correlation is expected between \( V_{PMT} \) and \( Q_1 - Q_0 \). The following measurements were performed:

\[
V_{PMT}[V] = \{1350, 1400, 1450, 1500, 1550, 1600\} \quad (2.8)
\]
\[
\times V_L[mV] = \{\text{no output}, 2500, 3000, 3500\} \quad (2.9)
\]

This limited range is a consequence of multiple factors. As the QDC has a resolution of the order 100 pC, the PMT needs a certain gain for photoelectron peaks to be distinguishable. Also the laser voltage is limited to lower values, retaining the probability of single photoelectron events. Note the difference between a single photon event and a single photoelectron event. The amount of photoelectrons created is a discrete probabilistic process, always allowing the emission of a single electron. Figure 2.10 shows the fitting results for \( V_{PMT} = 1500 \) V and different laser voltages.

The numerical results of the fitting of PMT1 are shown in table 2.2 and figures 2.11 and 2.12. The expected trends are present. The first one is the correlation between the mean number of incident photons \( \mu \) and the laser intensity. As the laser voltage is raised, the laser power rises. The increase in power will increase the laser emission and thus output intensity, which is directly related to the mean number of incident photons. The second trend concerns the correlation between the gain, measured by the amount of charge created per incident photoelectron, and the PMT voltage. According to the data sheet, the gain of each stage in the amplification section shows an exponential dependency on the applied voltage. That way
2.4 Trigger distribution

The distribution of the triggers, both in space and in time, is extensively recorded by the TDC module. By selecting the events in which two triggers were recorded of which the first was in the upper array and the second in the lower array, excluding the possibility of the coincidence of two noise pulses, only muons passing through both trigger arrays are retained. Using the positions of the triggered scintillators, the angle with which the muon passed through the tank can be measured. Figure 2.13(a) shows a the amount of events plotted against the bin difference, a measure for the horizontal separation between the first and the second trigger. Note that the order of the triggers was not checked, as both muons coming in from above and below the setup are allowed. To compare these results to the cosine-square distribution expected from muons, they had to be weighted. As a muon passing vertically through the

Figure 2.10: Fitted spectra of WLS PMT1 for $V_{PMT} = 1500V$ and different laser voltages.

an increase in supply voltage will directly increase the single photoelectron charge. For each of the two PMTs both trends are found. For future measurements, these results allow to deduce the amount of photoelectrons created within statistical errors.
setup could be measured on 8 positions, this bin was divided by a factor 8. A muon shifting one trigger bin was divided by a factor 7 and so on. The weighted results are represented by the black line in figure 2.13(b), where the weighted amount of events is plotted against the angle between the triggered scintillator bins. The errors on the angle are a consequence of the finite width of the scintillator bars and thus uncertainty on the exact positions. The blue line plotted is a cosine-square, scaled and shifted to the measurements, showing good agreement. Two remarks however have to be made. The first is that the cosine-square was shifted by approximately 0.1 radians or 5.73°. This may possibly be caused by the upper array not lying perfectly above the lower array. The second remark is that the solid angle of the scintillator bins was not taken into account. It can be expected that muons with a larger zenith angle have a smaller probability of crossing a scintillator and should therefore have a larger weight, make the curve flatter. This effect is possibly compensated by the longer path length inside the scintillator, leading to a higher probability of being detected.

The time between different trigger signals of one event is also recorded. Figure 2.14 shows the

Table 2.2: Mean number of photoelectrons $\mu$ and gain $Q_1 - Q_0$ for different measurements of WLS PMT1.

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>1350 V</th>
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<th>1500 V</th>
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<td>0.1323</td>
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<td>0.1319</td>
<td>0.1353</td>
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<td>0.9054</td>
<td>0.9955</td>
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<td>1.015</td>
</tr>
<tr>
<td>3500 mV</td>
<td>2.173</td>
<td>2.123</td>
<td>2.128</td>
<td>2.120</td>
<td>2.162</td>
<td>2.193</td>
</tr>
</tbody>
</table>

$Q_1 - Q_0$ [cts]

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<tr>
<td>3500 mV</td>
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<td>5.467</td>
<td>7.020</td>
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<td>11.140</td>
<td>13.780</td>
</tr>
</tbody>
</table>

Figure 2.11: Fitted results of $\mu$ for both WLS PMTs.
2.4. TRIGGER DISTRIBUTION

Figure 2.12: Fitted results of $Q_1 - Q_0$ for both WLS PMTs.

Figure 2.13: (a) Histogram showing the distribution of trigger angles, the measure on the x-axis represents the difference in bin position between the upper and lower trigger. (b) Graph showing the weighted version of the histogram plotted against the muon angle. The blue line represents a cosine-square function scaled and shifted to the measured values.

mean time between two following triggers as a function of the difference in bin position. The errors in the x-direction are again due to the width of the scintillator bars. The errors in the y-direction are based on the standard deviation of the gaussian fit of the measurements. The red line on the figure represents the speed of light, the blue curve is a straight line with the
same slope but shifted 0.33 ns downwards. All measurements but the last one show consistent with the blue line. However, the blue line represents a speed greater than the speed of light. A possible explanation is a difference in signal length of 0.33 ns from the array to the TDC between the upper and lower trigger array. This explanation is supported by the fact that the slope of the blue line equals the speed of light.

Figure 2.14: Mean time between two triggers as a function of the path length.

2.5 Summary

Both the scintillator trigger PMTs and the WLS PMTs had to be calibrated. Whereas of the trigger PMTs only temporal information was needed, telling whether a muon went through the scintillator or not, the WLS PMTs were calibrated absolutely. This absolute calibration entails information about the probability of creation of a photoelectron and the amount of charge created per photoelectron. Note however that this still does not allow to unambiguously classify a certain PMT response pulse as being caused by noise or a certain amount of photoelectrons, this is a consequence of the statistical nature of the processes.

By calibration of the trigger PMT voltage and CFD thresholds, all the rates were set between 2.30 Hz and 3.52 Hz. An additional check was performed by looking at the exact responses and fitting them to a Crystal Ball function. This brought up a discrepancy where no further attention was paid to.

The WLS PMTs were calibrated by using laser light and fitting their response to an extensive, well-substantiated PMT response function. The fitting procedure will be used in section 4.3 to interpret the Cherenkov light measurements.

An analysis of the trigger distribution is also performed. By demanding coincidence between the upper and lower trigger, the direction and crossing time of the incoming muon could be estimated. A cosine-square distribution was found back, correctly describing the angular muon distribution. The crossing time for different angles was consistently underestimated, presumably caused by a difference in signal length from the array to the TDC between the upper and lower trigger array.
Chapter 3

WOM setup simulation

A computer simulation of the experimental setup is created, aimed at providing a dissection of the physics inside the setup. In favor of elegance and efficiency of the simulation, not every single process or particle is reproduced but rather an abstraction is made. Thereto different estimations had to be considered about what are the dominant particles and processes. The primary goal of the simulation is to predict the output of the setup, allowing verification of the measurements. Further on, this simulation may be used to do a more extensive feasibility study, modeling more realistic WOM geometries and large arrays of WOMs.

3.1 Outline, parameters and abstractions

Geant4

The simulation makes use of the object-oriented Geant4 (GEometry ANd Tracking) toolkit, developed by the Geant4 Collaboration. It is the successor of the GEANT toolkits, developed by CERN. Its area of application not only includes high energy, nuclear and accelerator physics but also medical and space science. The toolkit is designed for the simulation of the passage of particles through matter, using Monte Carlo methods. The idea of a toolkit entails the usage of a pre-existing environment in which the simulation runs. Such an environment provides facilities for handling the geometry, tracking a particle and simulating detector responses, allowing the programmer to spend less time on low level details. To simulate the different particle and material interactions, Geant4 uses existing cross section and particle decay data sets.

Basic geometry and particle source

The basic geometry implemented is shown in figure 3.1. Only the parts influencing the measurement are constructed. Also shown on the figure is a juxtaposition of muon events showing tracks through the setup. All interactions are temporarily turned off in order to provide a clear image of the muons and their track. The muons are created by a simulated muon source, approaching the real cosmic muon spectrum. The source is characterised by its entrance position, angular distribution and energy spectrum. The entrance position is chosen randomly on the upper trigger surface, that way only the muons that can create a trigger signal are simulated. Measurements of the angular distribution of muons at sea level are shown in figure 3.2. The abstraction made for the simulation is based on a publication by M. Bektasoglu [59] posing that the zenith distribution of muons at sea level can be estimated to be in the form $I(\theta) = I(0)^\cos^n \theta$ with the exponent $n = 1.95 \pm 0.08$ for muons with momentum greater than 1 GeV. For the simulation, $n$ is set to two, leading to a $\cos^2 \theta$ dependency of the muon spectrum. Measurements of the muon energy spectrum are also shown in figure 3.2. The energy spectrum used for the simulation is based on these measurements. Only muons with an
energy of 0.1 GeV to 100 GeV are taken into account. The lower limit is justified by the limit for the production of Cherenkov light, $v > c/n$, saying that muons will only start producing Cherenkov light at kinetic energies above 0.055 MeV. The upper limit is deduced from the energy spectrum, showing that the muon flux decreases by almost 4 orders of magnitude of its maximum above 100 GeV.

To model the coincidence check of both trigger planes, each muon is tracked preliminary based on its initial position and direction - it is assumed that muons due to their high energy go through the tank without deviating much. Muons that do not cross the lower trigger plane are thrown away. The simulation shows that about 38% of the muons passing through the upper plane also passes through the lower plane.

Particles and interactions: restrictions

In favour of elegance and efficiency of the simulation, selections have to be made concerning the particles and interactions included in the simulation. By using the Geant4 environment all particles and processes can be in- or excluded with relative ease, allowing to check their significance. Concerning the particles, the first restriction is made by only simulating cosmic muons, neglecting all other cosmic and atmospheric particles. As shown in figure 3.3, the cosmic ray composition at sea level is dominated by muon neutrinos and muons, their fluxes being almost two orders of magnitude larger than the flux of the following particles, being protons and neutrons. The interaction probability of muon neutrinos is negligible in the setup and as they are chargeless they do not produce Cherenkov light. This justifies the simulation
3.1. OUTLINE, PARAMETERS AND ABSTRACTIONS

Figure 3.2: (a) Measured angular distribution of muons at sea level for different muon energies [60]. (b) Different measurements of the muon energy spectrum at sea level [61].

of only cosmic muons. Note that by working with the cosmic ray fluxes at sea level (Ghent lies at sea level plus 5-10 meters), the simulation of their origin (air showers etc.) is omitted.

Figure 3.3: Vertical fluxes of cosmic rays in the atmosphere with energy above 1 GeV. The markers show measurements of negative muons with energy above 1 GeV [54].
The next aspect taken under consideration is the muon decay. According to the Particle Data Group [54] the dominant (≈ 100%) decay mode is called the Michel decay and is due to weak interaction: \( \mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+ \). This decay sets the muon lifetime to \( \tau = 2.197 \mu s \). For a tank height of 0.25 m and a muon energy of 1 GeV, the time spent in the tank becomes \( \Delta \tau \approx 2.05 \text{ ns} \). This is much smaller than the muon lifetime and thus allows neglection of muon decay for the simulation.

To allow tracking of a muon through the water tank, its interactions with matter need to be investigated. These interactions are classically represented by the muon stopping power of materials, as shown on figure 3.4. The total stopping power (curve c) takes into account the electronic stopping power (curve a), caused by ionization and excitation of the medium, and multiple radiative processes (curve b), namely bremsstrahlung, \( e^+e^- \) pair production and photonuclear interactions [54]. As shown on the right in figure 3.4, for muon energies below 100 GeV electronic losses are dominant. Wielding a first order approximation, these are the only interactions of the muon taken into account. Concerning the particles, ionization directly imposes the inclusion of electrons in the simulation. Furthermore, excitation of the water can lead to scintillation light which should also be included.

![Figure 3.4: Muon energy losses in pure water as a function of muon energy. Curve a represents loss due to ionization and excitation of the medium, curve b represents loss due to all radiative processes and curve c represents the total energy loss [62].](image)

Last but not least the Cherenkov effect is included. Both muons and electrons resulting from ionization are high energy charged particles and they will produce Cherenkov light in the water tank. For illustration, figure 3.5 shows the setup simulating the Cherenkov cone and the ionization process for a 1 GeV incident muon. The angle to the particle direction under which the Cherenkov photons are emitted is given by \( \cos \theta_C = (\beta n)^{-1} \). For muons between 0.1 GeV and 100 GeV the angle will thus vary between respectively 29.77° and 41.24°.

To check on the assumptions made, different simulations are run including different processes. For each run a hundred 1 GeV muons traversing the tank in the middle are generated. The results are shown in figure 3.6. They show that it is justified to only include the Cherenkov effect and scintillation as these produce roughly all the photons. The Cherenkov effect produces about 80-90% of the total amount, scintillation is responsible for the others. As not only the amount but also the distribution of the photon directions is dependent on the processes, a second plot is made (figure 3.7). With different processes included, hundred 1 GeV muons
Results

The simulation was aimed at reproducing the processes inside the experimental setup, allowing to predict the measurements. These measurements however only provide very restricted insight in the exact mechanisms inside the tank, therefore a correct simulation is indispensable to gain a clearer insight into the setup and it will permit one to improve the experiment.

Scan of the WLS angle

The WLS bar can be rotated around its horizontal axis, the angle can thus be set such that as much photons as possible are captured. Simulations with the cosmic muon source are run for different angles of the WLS. The ratio of the amount of photons incident on the WLS to the total amount of photons produced is calculated, leading to the optimal WLS angle. The aim is of course capturing as many photons as possible. Figure 3.8 shows the results. As expected, the WLS captures the most photons when positioned horizontal. This is a consequence of the vertical cosine-square distribution of the incoming muons and hence of their Cherenkov cone.
Figure 3.6: Simulations for different muon energies, including different processes (CKV: Cherenkov effect, SCINT: scintillation, eBREM: electron bremsstrahlung, PP: muon pair production).

Figure 3.7: Logarithmic plot showing the distribution of the angle between the incoming muon and the created photons, simulated with hundred 1 GeV muons with different processes included.

Simulation of the detector tank

To simulate the full setup and the measurements, the WLS and WLS PMTs have to be implemented. This is where the first major simplification comes into play. The wavelength-shifting process is not simulated as such but use is made of effective measurements of the combined processes. The following spectra are used:

- **WLS capture efficiency** (WLS CE). This efficiency denotes the probability that an incident photon is captured, re-emitted and propagated to one of its two sides. The efficiency is derived from a publication by Lukas Schulte [48], providing results of a measurement of the capture efficiency of a similar WLS bar, fully read out on one side. For the purpose of this setup, the efficiency is rescaled by a factor five, as the WLS bar is read out on two sides and only one tenth of each side is read out.
3.2. RESULTS

Figure 3.8: Amount of photons incident on the WLS over the total amount produced, simulated for different WLS angles.

- **WLS emission spectrum** (WLS SP). When the WLS absorbs a photon it will be re-emitted following the distribution of the WLS emission spectrum.

- **PMT capture efficiency** (PMT CE). Efficiency describing the wavelength-dependent probability of absorption of a photon and creation of a photoelectron (PE) by the PMT.

Using these spectra, the probability is calculated that a photon, when incident on the WLS, creates a photoelectron in one of the two PMTs. First the probability of the creation of a photoelectron is calculated once it is absorbed by the WLS. This is a number independent of the incident photon wavelength and is given by the convolution of the PMT capture efficiency and the WLS emission spectrum. The calculation returns a probability of 0.1313. Afterwards, the complete WLS capture efficiency spectrum is multiplied with this number to provide the full probability of an incident photon on the WLS producing a photoelectron. Simulation of the absorption, re-emission and propagation mechanisms inside the WLS are omitted. The largest downside of this approach is that it neglects the position-dependence of the WLS to PMT capture efficiency.

In table 3.1 the primary results are shown. The main run consists of a $10^5$ events muon simulation of the full setup, calculating the amount of photons generated, the amount incident on the WLS and the amount captured by the PMTs. Another run of $10^5$ muons is performed with the WLS removed so that only photons directly incident on the PMT cathodes can be absorbed, the covers partly blinding the PMTs are still present. A third run is also performed without WLS and the PMTs uncovered. The following measures are calculated:

- **muons through lower trigger**. Represents the amount of muons, created on the upper trigger plane, going through the lower trigger plane. This amount is a consequence of the angular distribution of the muons.

- **photons/muon**. Represents the total amount of photons generated by the traversing muons.

- **photons to sensitive surface/muon**. Represents the part of the total amount of photons that reaches the sensitive surface of the setup, being either the WLS or the PMT cathodes. This measure is highly dependent on the geometry of the setup.
Figure 3.9: Figure showing the different spectra used to calculate the WLS+PMT capture efficiency, using the PMT capture efficiency (PMT CE), the WLS capture efficiency (WLS CE) and the WLS emission spectrum (WLS SP).

- **photons to PE/sensitive surface.** Represents the amount of photoelectrons (thus signal in the WLS PMT readout) created per photon incident on the WLS or PMT. This measure is dependent on the spectrum of the produced photons and the capture efficiency of the WLS and PMT.

- **photons to PE/muon (µ).** This is perhaps the most important measure. It represents the amount of photoelectrons created per passing muon and thus represents the efficiency of the detector.

The expected trends for the first two runs are present. Geometrically, a lot more photons are expected to be incident on the WLS bar (14% of total amount) than on the PMT cathode surfaces, either covered (0.016%) or uncovered (0.074%). One reason is the bigger surface, another is the better positioning towards a cosine-square source. Based on the capture efficiencies of the WLS+PMT and the WLS from figure 3.9, the different percentages of captured photons that create a photoelectron is also expected: 0.04% for WLS+PMT and 13.49% for PMT. These trends counteract each other, making the total efficiency comparable. The final efficiency $\mu$ is larger for the WLS system (1.792 PE per muon) than for the PMT system (0.61 PE per muon), this is mainly caused by the large and well-positioned sensitive surface of the WLS.

The last run shows a simulation of the setup with the PMTs uncovered, providing a larger sensitive area. As expected the percentage of the produced photons that reaches the PMT surface is raised a lot (a factor of 4.7), immediately resulting in a higher efficiency than for the run with the WLS. The main shortcoming of the WLS setup is the mismatch between the WLS and PMT spectra. The WLS emission peak is shifted to a wavelength where the PMT capture efficiency is lower (peak at 500 nm), reducing the effective increase in $\mu$ to a factor of
### 3.3. SUMMARY

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</table>

Table 3.1: Three simulations, $10^5$ muons generated, s.surf. denotes the sensitive surface being either the WLS or the PMT.

3. A measure for this mismatch is the probability of creation of a PMT photoelectron once the photon is absorbed. For the current WLS and PMT spectra this probability is 0.1313 (see spectral calculations at beginning of this section). To estimate the impact of the mismatch, the measurement is repeated using a different PMT, more sensitive to green light (PMT XP1981, [52]). The probability is increased to 0.153, thus increasing the capture efficiency by 16.5%.

### 3.3 Summary

The simulation encompasses many facets of the setup. A cosmic muon source was modelled based on data about the muon energy flux and angular distribution. The trigger response was approached by only creating muons in the upper array and demanding them to go through the lower array. This source will later be used for Monte Carlo simulations calculating the solid angles of the different scintillator bars. Note that only relative fluxes were taken into account. Per event one muon was generated according to the distribution but no time intervals were calculated between different muons. Using an absolute muon flux would allow to approach the temporal characteristics of the setup such as the different trigger rates.

Process-wise it was found that both the Cherenkov effect, caused by the muons but also ionized electrons, and scintillation in the water contribute most of the light picked up by the WLS PMTs (80-90% by Cherenkov, remaining part mainly by scintillation). It followed from these process considerations that muons, electrons and optical photons were the essential particles and were therefore the only ones included.

The wavelength-shifting process was not modelled but replaced by a Monte Carlo calculation based on the different spectra. It was found that on average per incident photon on the WLS with only 0.04% chance a photoelectron was generated, whereas this chance is 13% for the PMT cathodes used. The incidence on the WLS was naturally much higher than on the WLS PMT photocathodes, sitting in the side of the tank. The simulation allowed to calculate this amount, which is highly dependent on the detector geometry and spatial distribution of the processes - two things the distribution can calculate very precisely. Making further use of these calculations, the ratio of the amount of photons incident on the WLS over the total amount produced was predicted as a function of the WLS angle. It was found that for the WLS in vertical position this was only 60% of the case with the WLS in horizontal position, being 0.14.

To do a quantitative check between the experimental setup and the Geant4 simulation, different forms of the setup were simulated. These different forms could also be accomplished in the real setup, allowing to compare the trends of the WLS PMT responses. The most important
measure of the simulation was the expected amount of photoelectrons in the WLS PMTs per passing muon. For the setup with WLS this was found to be 1.792, showing a good efficiency. As the most important aspects of the Cherenkov light generation and capture are implemented, this simulation could in the future be used to simulate more realistic situations such as the implementation of WOMs in IceCube.
Chapter 4

Resume of the measurements

A full measurement is performed in four different settings:

- with WLS, WLS PMTs covered, full and empty tank
- no WLS, WLS PMTs covered, full and empty tank
- no WLS, WLS PMTs uncovered, full and empty tank

The PMT cover denotes the half circles that are placed around the WLS, covering the PMT photocathode part that is not covered by the WLS (figure 2.6). Some measurements are done without the covering in order to capture more Cherenkov light, thus allowing to check whether the setup is working correctly.

The setup as used in [49] is altered thanks to the acquirement of a TDC module. Previously an external coincidence check was performed between the upper and lower trigger array, confirming the passage of a muon through both trigger arrays and thus the tank. The TDC however allows to capture the individual trigger signals and timing of the 16 scintillator PMTs and check their coincidence afterwards, providing more freedom and insight in the processing of the measurements. In short, this means that the setup will be triggered as soon as one scintillator PMT produces a trigger. Thereafter the TDC will search for accompanying trigger signals inside a certain time window, checking whether other scintillator PMTs went off. At the same time the charges of both WLS PMTs are read out by the QDC. After the measurements, cuts on the events will be made, retaining only the events that are sought after.

4.1 Full and empty tank - verification of signal origin

The first measurements aim at checking whether the setup functions as expected. Furthermore estimates are made of pulse timings using an oscilloscope and delays are added where needed. Essentially two 12 hour measurements are performed, one with a full tank and one with an empty tank. Due to the low refractive index of air \(n_{\text{air}} = 1.000293\), the Cherenkov effect in the empty tank is negligible. The only charge observed in the WLS PMTs is caused by noise in the PMTs and possibly some scintillation light produced by traversing particles. Comparison of the measurements between the full tank and the empty tank should therefore allow to prove the production and detection of Cherenkov light.

Figure 4.1 shows a measurement of the charge spectrum of WLS PMT 1 for a full tank. No cuts have been performed on the events yet. A fitting of the PMT spectrum to the PMT response function described in section 2.3.2 is performed. Two peaks are clearly distinguishable. The first and highest peak is the pedestal peak, centered around \(Q_0 = 94.36\) counts. This peak denotes the PMT charge when no light is captured. A second peak is seen at \(Q_1 = Q_0 + 21.22\) counts. Based on the calibration and fitting this is ascribed to single-photon-electron (1PE) emission. Figure 4.2 shows the same measurement but for an empty tank. As the Cherenkov
effect in air is negligible, no charge is expected in the WLS PMTs. The figure shows that the 1PE peak is indeed 2 orders of magnitude smaller than was the case for a full tank. The most quantitative measure to check this is the fitting result of $\mu$, the mean number of collected photoelectrons per event. Taking only the 1PE peak into account, $\mu$ represents the ratio of the PE peak over the pedestal peak. For a full tank this is $\mu_{\text{full}} = 0.041 \pm 0.001$ whereas for an empty tank this is $\mu_{\text{empty}} = 0.00016 \pm 0.0001$. Taking into account the duration of the measurement, being approximately 2200 seconds, and the maximum noise rate of 0.1 Hz this peak can at first sight be ascribed to noise. Another possibility is the capture of scintillation light in air or some occasional Cherenkov light.

Figure 4.1: QDC spectrum of WLS PMT 1 for a full tank and the PMTs uncovered. Left: full measurement plotted against a logarithmic scale. Right: Normalized plot of the distribution.

Figure 4.2: QDC spectrum of WLS PMT 1 for an empty tank and the PMTs uncovered. Left: full measurement plotted against a logarithmic scale. Right: Normalized plot of the distribution.

Based on the PMT response function a third peak, the two-photoelectron (2PE) peak, is predicted. This peak is also found back in the measurement of the full tank but seems
underestimated. As this shortcoming was also found back in later measurements, the PMT response function was adapted. A new parameter was introduced, allowing separate scaling of the third peak. To compensate for the increase of the 2PE peak, the original curve should also be rescaled, introducing yet another parameter \( N \) (representing the amount of events under the original curve). As figure 4.3 shows, the 2PE peak is rescaled with a factor 5.5 and approximates the measured curve a lot better. Later the reason for the underestimation of the 2PE peak in the general PMT response function was resolved. Initially \( \mu \) represented both the ratio of emission of 1PE over the 0PE (pedestal curve) and the ratio of emission of 2PE over 1PE, 3PE over 2PE etcetera. These ratios however have to be decoupled as the pedestal peak also encompasses events where no photon was captured by the PMT, making it representable for the detector efficiency. The second ratio however represents the likelihood of creating two versus one photoelectrons, only when at least one photoelectron is created. This ratio is higher than the first one, explaining the underestimation.

![Figure 4.3: QDC spectrum of WLS PMT 1 for a full tank with improved PMT fitting function. The 2PE peak is better approximated.](image)

### 4.2 Scintillator threshold scan

The next measurement applies to the scintillator trigger threshold, as applied by the CFD module. A measurement is highly dependent on this value as it sets a threshold on the minimal amount of scintillation light. Furthermore it sets the trigger rate. If the threshold is too high, the amount of events might be too low to interpret. If the threshold is too low, scintillator and PMT noise will dominate the measurement. Figure 4.4 shows measurements over a large range of threshold values of the amount of events and the trigger efficiency. The trigger efficiency is defined as the ratio of the amount of events where light is captured, by any or both of the WLS PMTs, over the total amount of events. To decide whether a PMT captured light or not, its charge is discriminated to be either above (in the 1PE peak) or below (in the pedestal peak) the minimum between the two peaks.

The first measurement shown in figure 4.4 represents a scan of 1 hour measurements performed over a large range of threshold voltages. The black markers represent the total measurement. On the upper figure, the trigger efficiency is plotted. The efficiency shows saturation starting between 20 mV and 30 mV. The interpretation of this is that before the platform the ratio of good triggers (triggers paired with light in the WLS PMTs, as opposed to false triggers)
over the total amount of triggers is lower than on the platform. This can be explained by the fact that noise pulses from the scintillator PMTs are being picked up which are random and uncorrelated to any light in the WLS PMTs. This is to be avoided. Once on the platform, the curve stays approximately flat. Assuming that the scintillation light yield and thus scintillator PMT response is correlated to the muon energy\(^1\), this means that the detector efficiency does not increase with higher muon energies. Looking back at the simulation, figure 3.6 shows that the amount of photons generated per muon does not increase for energies above 1 GeV. This can be related to the measurement as apparently no increase in detection efficiency is found for higher energetic muons. Calculation of the black curve still uses all of the events, triggered by either or both of the trigger arrays. However, aiming at improving the trigger efficiency, a cut was applied demanding coincidence of the upper and lower trigger array. This measure should allow first of all a stern lowering of random noise pulses of the scintillator PMTs and secondly removal of the triggers created by particles that are absorbed in the tank or exit sideways. The severity of the cut can be seen in the lower part of figure 4.4, showing a decrease in the amount of triggers of one to three orders of magnitude. As the rate already drops a lot upon raising the CFD threshold, starting from 60 mV extra extended (6 hour) measurements were performed to improve statistics. The results are shown by the red (1 hour) and blue (6 hour) curve. The trigger efficiency is expected to increase upon performing this cut, a tendency that can be found by the red curve. The new measurements however do not show this behaviour until 110 mV. One possible explanation is that below 110 mV the energy of the muons can still be low enough for them to be absorbed by the water tank but after creating light, creating a signal in the WLS PMTs but not fully traversing the setup.

4.3 WLS PMT measurements

Four measurements are discussed in this section: with and without WLS in a full and empty tank. Each measurement is represented in a figure consisting of a left and a right plot. The left plot shows a histogram containing all the triggered events, their QDC value and the fitted PMT response, plotted against a logarithmic y-axis. As the length of the measurements varies, so does the total amount of events, preventing comparison of the peak heights. Therefore on the right plot the measurement is shown again, normalized to 1.

The first two measurements, of the full tank with and without WLS, are shown in figures 4.5 and 4.6. Qualitatively it is easily seen from the right plots that the 1PE peak of the full tank with WLS is almost a factor 4 higher than the case without WLS. Quantitatively the mean amount of photoelectrons per event \(\mu\) for the full tank with WLS is \(\mu(\text{full},\text{WLS}) = 0.0397 \pm 0.0003\) and for the full tank without WLS \(\mu(\text{full},\text{noWLS}) = 0.01255 \pm 0.00011\), less than a third of \(\mu(\text{full},\text{WLS})\). The other parameters of the fitting are bound to the bare PMT characteristics rather than to the yield of the measurements. Confirmingly they barely deviated from each other and from the PMT calibration in section 2.3.2.

The last two measurements, of the empty tank with and without WLS, are shown in figures 4.7 and 4.8. Again the measurement with WLS shows a much higher light capture rate than the one without WLS. In this case \(\mu(\text{empty},\text{WLS}) = 0.00633 \pm 0.00015\) and \(\mu(\text{empty},\text{noWLS}) = 0.000231 \pm 0.000016\), more than 25 times smaller. The deviation of the other fitting parameters between both plots is larger than in the full tank case. This is assumed to be caused by a lack of statistics in the empty tank measurement, disturbing the fitting.

The most important results are shown in table 4.1. The results show the tendencies that were expected. What does strike is the fact that the ratio \(\mu(\text{empty},\text{noWLS})/\mu(\text{empty},\text{WLS}) = 0.036\) is much smaller than is the case with a full tank \(\mu(\text{full},\text{noWLS})/\mu(\text{full},\text{WLS}) = 0.32\). This

\(^1\)The scintillation light yield is proportional to the energy deposited by the muon. According to [54] the stopping power increases with the energy starting from 0.05 GeV so the assumption can be justified.
4.3. WLS PMT MEASUREMENTS

Figure 4.4: Measurements of the trigger efficiency and rate as a function of the scintillator threshold voltage.

might be traced back to the fact that the generated light gets scattered more easily by the water in the full tank. This would allow it to deviate and propagate more sideways into the small PMT slits\(^2\).

The simulation, previously discussed in section 3.2, was run for three cases, namely the full tank with WLS, without WLS and without WLS and PMT covers. The measurements of WLS PMT1 of these cases are shown respectively in figures 4.5, 4.6 and 4.3. For comparison the efficiency of WLS PMT1 and WLS PMT2 should be added, as was the case for the simulation. In table 4.2 and figure 4.9 the simulated and total measured results are compared. The y-axis of the figure is plotted logarithmically to show the proportionality between the results. The measured efficiency seems to be a factor 23 to 33 lower than the simulated one. One explanation is an increased amount of losses in the real setup, caused by e.g. refraction on the WLS and PMT surfaces, not taken into account in the simulation. Another explanation blames this on false triggers, triggering when no real muon is passing, whereas the simulation

\(^2\)When the WLS is removed and the cover around the WLS opening remain, only a small slit of the PMT is exposed to the tank. Its cross-section is even further lowered by the fact that the covers have a thickness of about 1 cm, decreasing the angle from which photons can reach the PMT cathode surface.
assumes a perfect trigger. If this were the case then the proportionality factor between \( \mu(\text{meas}) \) and \( \mu(\text{sim}) \) represents a measure of the efficiency of the trigger.

### 4.4 Cuts on the events

When any of the 16 trigger channels generates a signal, the TDC module searches within a certain time window whether any of the other channels also generated a trigger. As muons are expected to cross the tank easily, they will generate a scintillation pulse both in the upper and the lower array. Using the TDC these events can be selected, cutting out events where only one array was triggered (particle absorbed in the tank, exited sideways or noise pulse). The remaining events presumably create more light in the tank and thus increase the WLS PMT light capture.
4.4. CUTS ON THE EVENTS

Light yield

The following two cuts were tried:

- cut 1: number of triggers equals 2 and one trigger in upper array, one trigger in lower array
- cut 2: demand tighter timing - time between triggers smaller than 5 ns

Using as illustration the 6 hour measurement performed on the full tank with WLS, these cuts reduce the amount of events to roughly 2% for cut 1 and 5% for cut 3 of the total amount of events. Fitting of the QDC spectrum however does not show an improvement of $\mu$. This seems to point at a suppressed or lack of correlation between the WLS PMT response of an event and the amount and position of its triggers. Note that correlation between the timing of the trigger and the light production was confirmed by moving the time of the measurement of the WLS PMTs, retrieving a much lower $\mu$. It is the amount of light produced, assumed correlated...
### CHAPTER 4. MEASUREMENTS AND CALIBRATION

#### Table 4.1: Results from the fitted measurements.

<table>
<thead>
<tr>
<th></th>
<th>WLS PMTs covered</th>
<th>no WLS PMTs covered</th>
<th>WLS PMTs uncovered</th>
<th>no WLS PMTs uncovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu ) (meas)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WLS PMT1</td>
<td>0.0397 ± 0.0003</td>
<td>0.01225 ± 0.0001</td>
<td>0.00633 ± 0.0002</td>
<td>0.0002306 ± 0.00002</td>
</tr>
<tr>
<td>WLS PMT2</td>
<td>0.0364 ± 0.0003</td>
<td>0.01024 ± 0.0001</td>
<td>0.00450 ± 0.0001</td>
<td>0.0001319 ± 0.00002</td>
</tr>
</tbody>
</table>

#### Table 4.2: Comparison of the measured value for \( \mu \) and the simulated one.

<table>
<thead>
<tr>
<th></th>
<th>WLS PMTs covered</th>
<th>no WLS PMTs covered</th>
<th>no WLS PMTs uncovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu ) (meas), total</td>
<td>0.0761 ± 0.0006</td>
<td>0.02249 ± 0.00021</td>
<td>0.08263 ± 0.00210</td>
</tr>
<tr>
<td>( \mu ) (sim)</td>
<td>1.7915</td>
<td>0.6068</td>
<td>2.7668</td>
</tr>
<tr>
<td>( \mu ) (meas)/( \mu ) (sim)</td>
<td>0.0425</td>
<td>0.0371</td>
<td>0.0299</td>
</tr>
</tbody>
</table>

#### Figure 4.9: Logarithmic plot of \( \mu \) (real) and \( \mu \) (sim) for the three setups (1: WLS and PMT covered, 2: no WLS and PMT covered, 3: no WLS and PMT uncovered).

To \( \mu \), that does not seem directly related to the amount of trigger and their positions. For completeness the results are presented in table 4.3.

#### Table 4.3: Results of the cuts on a 6 hour measurement of the full tank with WLS.

<table>
<thead>
<tr>
<th></th>
<th>no cut</th>
<th>cut 1</th>
<th>cut 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>retained events</td>
<td>1214584</td>
<td>27170 (0.0224)</td>
<td>38539 (0.03173)</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.03790</td>
<td>0.03590 ± 0.000010</td>
<td>0.03858 ± 0.000010</td>
</tr>
</tbody>
</table>

By making one assumption, an explanation is proposed. The assumption states that each trigger signal is caused by a muon. The assumption can be substantiated by the fact that the measured dark PMT noise does not exceed a 0.1 Hz trigger rate, held against a minimal scin-
4.4. CUTS ON THE EVENTS

tillator trigger rate of 2.4 Hz, allowing the neglection of noise triggers. Furthermore assuming that no other particles are triggered is based on the same arguments as were brought up for the simulation in section 3.1, mainly relying on figure 3.4. On the basis of this assumption, the uncorrelation of the amount of triggers and the light produced can be traced back to a low scintillator trigger efficiency. This would imply that the absence of for instance the lower trigger in an event does not indicate that the crossing particle was not a muon or that it was absorbed in the tank, it merely indicates that the lower trigger array did not detect the muon. The amount of scintillators that were triggered would no longer be correlated to the identity or energy of the particle and thus to the amount of light produced. As explained in the following section, this assumption allows calculation of the scintillator trigger efficiency from the measurements.

Calculation of the scintillator efficiency

The above made assumption allows deduction of the scintillator trigger efficiency from the measurements. For each upper trigger signal a muon then will either cross one of the lower array scintillators or leave the setup sideways, the ratio of which can be calculated. As the measured amount of upper trigger signals accompanied by a lower trigger signal follows from the first of the above-mentioned cuts, the efficiency can be calculated. First the probability of an upper triggered muon passing through one of the lower array scintillators is calculated using the simulation. This represents the solid angle of the lower scintillator bin, as seen by a muon crossing a certain upper bin.

![Figure 4.10: Figure showing the solid angle as a function of bin difference.](image_url)

<table>
<thead>
<tr>
<th>bin difference</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>probability</td>
<td>0.1457</td>
<td>0.0800</td>
<td>0.0457</td>
<td>0.0295</td>
<td>0.0196</td>
<td>0.0132</td>
<td>0.0089</td>
<td>0.0062</td>
</tr>
</tbody>
</table>

Table 4.4: Table showing the probability of a muon triggered in the upper bin going through a lower bin for different bin separations.

To calculate the efficiency of a scintillator bar one upper scintillator bin is chosen and only the events in which this scintillator was triggered are retained. Based on the above-mentioned
probability calculations, the expected amount of muons per lower scintillator bin can be calculated. By then looking at the measured amount of triggers in the retained events, thus coming from the chosen upper scintillator, an estimation of the lower trigger bin efficiency can be calculated. As only one upper scintillator bin is used, this calculation can be repeated eight times, lowering the error. Figure 4.11 shows the results of the eight efficiency calculations for each lower bin. The x-axis represents the zenith angle between the upper bin, used for the calculation, and the lower bin, whose efficiency is calculated (zenith angle $\theta$ shown on figure 4.10). A flat line was expected, representing different measurements of the same efficiency. However, consistently through the measurements, an increase of the efficiency with the zenith angle was found. The trend holds a cosine-like angular dependence as can be seen by the fitted cosine, represented by the red curve. This can be traced back to an erroneous solid angle, deviation of the detected muons from the cosine-square law (indicating that they are of energies above 10 GeV), anisotropy in the trigger efficiency or another error in the calculations. Unfortunately the issue could not be immediately resolved.

![Figure 4.11: Scatter plot showing efficiencies of the lower scintillator bins, plotted against the angle of the upper scintillator bin used for the calculation.](image)

### 4.5 Summary

Measurements of the full setup, encompassing the trigger system combined with readout of the WLS PMTs, were presented in this section. First a verification of the WLS PMT signal origin was performed. By doing a specific measurement both for a full and an empty tank, it could be verified that the charge found back was effectively caused by Cherenkov light (and a minor part scintillation light in the water).

A scan was performed over different scintillator trigger thresholds, expecting to see an increase of Cherenkov light upon demanding an increase of scintillator light. This was not found back unambiguously. Starting from a small threshold a platform was found back with an almost constant detector efficiency of about 0.12. Upon demanding coincidence between the upper and lower trigger, an increase in the efficiency was found back at high thresholds. This could however be caused by the large decrease of events and thus statistics by asking coincidence. An analysis of the trigger distribution was also performed.
In total, measurements of the full setup in six different forms were performed: with WLS, without WLS and without PMT covers, each for a full and an empty tank. For each measurement fitting of the WLS PMT response gave the expected tendencies in light yield. Comparison with the simulated responses shows that the measured efficiencies are a factor 23 to 33 lower than the simulated ones. Possible explanations thereof are large losses at the WLS and PMT surfaces or the generation of false triggers.

Note that for all the above measurements only one trigger signal was demanded, omitting the coincidence check between the upper and lower array. This was a consequence of an analysis done before the processing of the measurements. It was observed that upon asking coincidence between the upper and lower array, no increase in the amount of light detected was found. This contradicted the expectation as the coincidence condition cuts out the largest part of the false triggers. An explanation is provided based on the assumption that each trigger signal is created by a passing muon, neglecting noise triggers and other particles. This explanation furthermore brings up a method allowing to calculate the efficiency of the scintillator counters used, a property otherwise difficult to measure.
Chapter 5

Closure - results and outlook

In retrospect, the research performed consisted of three main parts. These were the creation of a simulation of the setup, calibration of the setup and performing and interpreting measurements on the setup. Each of them took up about the same amount of time.

In order to write a decent simulation without blankly including all processes and particles, a study was performed aimed at estimating what are the dominant mechanisms in the setup. As expected the main particle flux can be ascribed to muons and is in the region of 0.1 GeV to 100 GeV best approached using a cosine-square distribution. Upon passage they produce both Cherenkov (80-90%) and scintillation light and the little energy they lose is due to the ionization of the water. Multiple other processes were included to check their influence but they were found to be negligible. Next the wavelength-shifting bar (WLS) and photomultipliers (PMTs) were implemented making use of their published capture and emission spectra, omitting the full simulation of the WLS and PMT mechanisms. The simulation allowed a close follow-up of how and where the photons were produced, their propagation in the tank and whether and where they were absorbed. It was shown that the freedom in geometry of the WLS can easily lead to an improvement of the amount of photons captured compared to a photocathode surface, more limited both in size and shape. The improvement however showed to be easily negated by the narrow capture efficiency of the WLS. This effect is even reinforced in the used setup due to a mismatch between the WLS emission peak and PMT absorption peak. The probability of detection of a photon incident on the WLS was found to be 0.04%, opposed to 13% on the bare PMT. Lastly the simulation predicted the setup to be 100% efficient, expecting 1.79 photoelectrons to be generated per passing muon with an energy between 0.1 GeV and 100 GeV.

The calibration of the setup refers to both the calibration of the trigger arrays and the calibration of the PMTs reading out the WLS. The former was performed by aiming at a uniform detection rate for all the different scintillator bars forming the trigger. By assuming both the flux and scintillator response to be constant across the arrays, a uniform rate would exclude any muon energy or position bias from the trigger. The final rates were all set between 2.30 Hz and 3.52 Hz, well above the dark noise rate and below the expected muon flux per bar, being approximately 10 Hz. For the WLS PMTs a different approach was taken. By using a laser to illuminate the photocathode, extensive measurements of the PMT spectrum were performed over a large range of both laser and PMT voltages. These measurements were fitted to a published PMT response function, disclosing the different PMT characteristics such as gain and efficiency.

The final hatch concerned the measurements and interpretation of the muon Cherenkov light. By doing the same measurement both with a full and an empty tank it was assured that the light picked up was generated in the water, combined with the simulation this confirmed the detection of Cherenkov light. Measurements were performed using different settings of the setup, allowing to check on expected tendencies and compare with the simulation. Using the
WLS PMT calibration quantitative measurements of the amount of light produced could be made, showing the expected tendencies. The efficiencies were found to be a factor 23 to 33 lower than the simulated ones. This is mainly blamed on photon losses not taken into account in the simulation, e.g. refraction losses at the sensitive surfaces. The usage of a time-to-digital (TDC) module, recording when and where triggers went off, allowed a close analysis of the trigger distribution. Using the spatial information the cosine-square distribution of the incoming muons was found back. The timing information proved the muons to move through the setup at the speed of light, neglecting a consistent underestimation of the crossing time. This was blamed on a difference in path length to the TDC between the upper and lower array. When comparing events in which both trigger arrays went off opposing to events where only one trigger went off, an increase in efficiency of the setup was expected. This was based on the cutting out of false triggers caused by noise and muons exiting sideways or getting absorbed in the tank, producing less or no Cherenkov light. This was not found back. It lead to the belief that the events cut out lacked a lower trigger due to failure of the trigger, rather than the above mentioned reasons. Based on this assumption a method was developed to calculate the efficiency of the lower triggers. By assuming that on each trigger of the upper array a muon passed through that specific bar, the expected amount of muons through each of the lower trigger bars can be calculated, based on its solid angle and the angular muon distribution. Using the triggers recorded per event by the TDC, the number that was found back can be compared to the calculated number of expected muons, leading to the detection efficiency of each of the bars. The method was applied to the used triggers but the efficiencies showed a cosine-like dependency on the zenith angle. This is possibly caused by an anisotropy in the trigger efficiency related to the path length of the muons. It could however not be immediately resolved.
Appendix A

Convoluted response

\[
S_{\text{real}}(x) = S_{\text{ideal}} \otimes B(x) = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} [(1 - w)G_n(x - Q_0) + wI_{G_n \otimes E}(x - Q_0)] \quad \text{(A.1)}
\]

\[
e^{-\mu} \left[ \frac{1 - w}{\sigma_0 \sqrt{2\pi}} e^{-\frac{(x - Q_0)^2}{2\sigma_0^2}} + w\theta(x - Q_0)\alpha e^{-\alpha(x - Q_0)} \right] \quad \text{(A.2)}
\]

\[
+ \sum_{n=1}^{\infty} \frac{\mu^n e^{-\mu}}{n!} [(1 - w)G_n(x - Q_0) + wI_{G_n \otimes E}(x - Q_0)] \quad \text{(A.3)}
\]

with

\[
I_{G_n \otimes E}(x - Q_0) = \int_{Q_0}^{x} G_n(x' - Q_0)\alpha e^{-\alpha(x-x')} \quad \text{(A.5)}
\]

\[
= \frac{\alpha}{2} e^{-\alpha(x - Q_0 - \alpha\sigma_n^2/2)} \left[ \text{erf} \left( \frac{|Q_0 - Q_n - \sigma_n^2\alpha|}{\sigma_n \sqrt{2}} \right) \right] \quad \text{(A.6)}
\]

\[
+ \text{sign}(x - Q_n - \sigma_n^2\alpha) \text{erf} \left( \frac{|Q_0 - Q_n - \sigma_n^2\alpha|}{\sigma_n \sqrt{2}} \right) \quad \text{(A.7)}
\]

\[
Q_n = Q_0 + nQ_1 \quad \text{(A.8)}
\]

\[
\sigma_n = \sqrt{\sigma_0^2 + n\sigma_1^2} \approx \sigma_0, \quad n = 0 \quad \text{(A.9)}
\]

\[
\approx \sqrt{n}\sigma_1, \quad n > 0 \quad \text{(A.10)}
\]
Appendix B

Results WLS PMT 2

Figure B.1: Fitted spectra of WLS PMT2 for $V_{PM} = 1500V$ and different laser voltages.
### Table B.1: Mean number of photoelectrons $\mu$ and gain $Q_1 - Q_0$ for different measurements of WLS PMT2.

<table>
<thead>
<tr>
<th>$u$</th>
<th>1350 V</th>
<th>1400 V</th>
<th>1450 V</th>
<th>1500 V</th>
<th>1550 V</th>
<th>1600 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>0.006472</td>
<td>0.006899</td>
<td>0.007260</td>
<td>0.007899</td>
<td>0.007682</td>
<td>0.007715</td>
</tr>
<tr>
<td>2500 mV</td>
<td>0.1544</td>
<td>0.1643</td>
<td>0.1727</td>
<td>0.1711</td>
<td>0.1784</td>
<td>0.1775</td>
</tr>
<tr>
<td>3000 mV</td>
<td>0.9731</td>
<td>1.016</td>
<td>1.056</td>
<td>1.070</td>
<td>1.096</td>
<td>1.107</td>
</tr>
<tr>
<td>3500 mV</td>
<td>2.038</td>
<td>2.074</td>
<td>2.192</td>
<td>2.271</td>
<td>2.272</td>
<td>2.310</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Q_1 - Q_0$ [cts]</th>
<th>1350 V</th>
<th>1400 V</th>
<th>1450 V</th>
<th>1500 V</th>
<th>1550 V</th>
<th>1600 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 mV</td>
<td>5.164</td>
<td>6.656</td>
<td>8.597</td>
<td>11.100</td>
<td>14.080</td>
<td>17.790</td>
</tr>
<tr>
<td>3000 mV</td>
<td>5.088</td>
<td>6.527</td>
<td>8.521</td>
<td>10.940</td>
<td>14.030</td>
<td>17.750</td>
</tr>
</tbody>
</table>
Verbeteren van de IceCube gevoeligheid met een wavelength shifting optische module

Simon Apers

Samenvatting—Het onderzoek gepresenteerd in deze paper is gericht op het onderzoeken van de mogelijkheid tot gebruik van een wavelength shifter als gevoelig oppervlak voor de detectie van Cherenkov licht. Daartoe is een experimentele opstelling gebruikt in combinatie met een Geant4 simulatie van de opstelling. Een uitgebreide calibratie bevestigde de detectie van Cherenkov licht en liet toe de efficiëntie van verschillende metingen onderling te vergelijken, verder onderbouwd door de simulatie. Aanvullend werd op basis van de opstelling een methode voorgesteld die toelaat de anders verholen efficiëntie van de gebruikte triggers te berekenen.

Indextermen—WLS, Cherenkov detector, IceCube, Geant4.

I. HET ICECUBE NEUTRINO OBSERVATORIUM

Het IceCube Neutrino Observatorium is een neutrino-telescoop gestationeerd op de Zuidpool, alwaar het gebruik maakt van een kubieke kilometer ijs als detectiemedium. Door het opvangen van Cherenkov straling, geproduceerd door het voorbijkomen van geladen deeltjes, worden aanwijzingen gevonden omtrent de afkomst van de hoogst energetische kosmische straling. In zijn huidige toestand kan het observatorium indirect neutinos detecteren met energieën van 10 tot $10^{15}$ GeV. Deze limiten worden bepaald door de resolutie van de detector, deze wordt op zijn beurt bepaald door de efficiëntie van het detecteren van Cherenkov straling. Dit is de reden waarom IceCube voortdurend tracht zijn detectie-instrumentatie te verbeteren, wat tevens de aanleiding is van dit onderzoek.

II. DETECTIE VAN CHERENKOV STRALING: OPTISCHE MODULES

Momenteel gebruikt IceCube 5160 Digitale Optische Modules (DOMs) ingekapseld in het ijs, gericht op het detecteren van Cherenkov licht. Dit zijn glazen bollen die een fotokathode bevatten als actief oppervlak. De vangstefficieëntie van fotokathodes licht heel hoog maar ze zijn erg kostelijk en produceren veel ruis. Deze laatste kunnen problematisch worden bij het vergroten van de fotokathodes, gericht op het verhogen van de IceCube resolutie. Dit heeft geleid tot het ontwerp van een alternatieve module gebaseerd op passieve wavelength shifting materialen, een zogenaamde Wavelength shifting Optische Module (WOM). Figuur 1 toont een ontwerp gepubliceerd door Lukas Schulte. Het primaire idee is het scheiden van enerzijds het vangen van licht en anderzijds het omzetten van dit licht naar een detecteerbaar signaal. Het vangen van licht moet door een zo groot mogelijk oppervlak gebeuren terwijl het omzetten van het licht gebeurt door een fotokathode, daarvan moet het oppervlak dus zo klein mogelijk gehouden worden. In het geval van een WOM wordt de lichtcollectie uitgevoerd door een wavelength shifter (WLS), dit is een materiaal dat fotonen absorbeert en het opnieuw uitzendt aan een langere golflengte. Totale interne reflectie in het materiaal zorgt ervoor dat een groot deel van het heruitgezonden licht gevangen blijft in het materiaal en zo naar een uiteinde propageert. Daar wordt het licht gebundeld en naar een veel kleinere fotokathode geleid. De ruis wordt een factor 80 lager verwacht dan voor een DOM het geval is. Dit onderzoek is gericht op het experimenteel onderschrijven van het gebruik van een WLS om Cherenkov licht te vangen.

III. WOM OPSTELLING

De opstelling bestaat uit een tank van 168 l water die een 10 cm x 0.5 cm x 80 cm WLS staaf bevat, horizontaal geplaatst op een vijfde van de hoogte van de tank. Boven en onder de
tank zijn een reeks scintillator staven geplaatst,
dewelke elk apart uitgelezen worden door een fotomultiplicator (PMT). De scintillatoren dienen
als trigger voor voorbijkomende muonen. Bij het ontvangen van een trigger signaal worden beide
kanten van de WLS uitgelezen door een PMT. Ter vergelijking worden alle metingen uitgevoerd
voor zowel de opstelling met WLS als zonder, in het laatste geval kunnen enkel de fotonen die
rechtstreeks de twee smalle WLS PMTs bereiken worden gedetecteerd.

IV. SIMULATIE VAN DE OPSTELLING
Een simulatie van de opstelling is geschreven,
gebruik makend van de Geant4 toolkit. Met
de geometrie en de materialen geïmplementeerd
werd een muon bron gecreëerd, zo dicht moge-
lijk aaneenleunend tegen de werkelijke omstandig-
heden. Uit de simulatie volgt dat de dominante
processen in de tank muon ionisatie, het Che-
renkov effect en scintillatie in het water zijn.
Als een gevolg werden enkel muonen, elektronen
en fotonen gesimuleerd. Het wavelength shifting
proces in de WLS werd niet gemodelleerd maar
vervangen door een Monte Carlo berekening
gebaseerd op gepubliceerde vangst- en emissie-
spectra. Er is gevonden dat invallende fotonen op
de WLS gedetecteerd wordt met een waarschijnlijkheid
van 0.04% tegenover 13% direct op de PMT.
Dit is een gevolg van het kleine absorptievenerster
van de WLS en het emissiespectrum dat niet
gematcht is aan de PMT. Specifiek voor de
opstelling werd dit effect gemakkelijk gecomp-
penseerd door het aantal invallende fotonen op
het oppervlak per muon, dat bijna een factor
900 groter is voor de WLS dan voor de kleine
fotokathodes. Door dit effect is het aantal foto-
elektronen \(^2\) (PE) gecreëerd per voorbijkomend
muon 1.79PE voor de opstelling met WLS, wijz-
zend op een 83% efficiënte detector\(^3\), tegenover
0.61PE zonder WLS of een 54% efficiënte de-
tector.

Met de belangrijkste mechanismen geprogram-
meerd kan de simulatie in de toekomst gebruikt
worden voor het modelleren van meer realisti-
sche situaties zoals de implementatie van een
WOM in IceCube.

V. CALIBRATIE VAN DE OPSTELLING
De opstelling gebruikt twee sets van PMTs, de
eerste voor het uitlezen van de trigger scintillato-
en en de tweede voor het uitlezen van de WLS. Aangezien de scintillator PMTs enkel gebruikt
worden om een triggersonaal te genereren is
hun exacte respons niet van belang. Bijgevolg
wordt enkel de trigger frequentie gecalibreerd.
Deze frequentie wordt bepaald door het voltage
over de PMT en de threshold check uitgevoerd
door de CFD uitleesmodule, die de eigenlijke
trigger produceert. Uiteindelijk werden alle trigg-
er frequenties tussen 2.3 Hz en 3.5 Hz gezet,
ruim boven de PMT ruis frequentie en onder de
verwacht muon flux, zijnde 10 Hz per scintillator.

Betreffende de respons van de WLS PMTs werd
een meer diepgaande analyse uitgevoerd, die ook
definieerde hoeveelheid lading die gecreëerd
wordt in rekening brengt. Voor de calibratie werd
een laseraan met variabele intensiteit gebruikt.
Door de statistische aard van de PMT werking
worden grote hoeveelheden metingen gedaan die
vervolgens toelaten daar een algemene PMT
response aan te fitten. De karakteristieken van
de PMT volgen dan uit de gefitte functie. Figuur
2 toont een fit aan het ladingspectrum van een
PMT belicht door een laseraan, voor een meting van
2 \( \times 10^5 \) events. De discrete PMT pieken worden
teruggevonden en een welgedefinieerde correla-
tie tussen het aantal foto-elektronen gecreëerd en
de intensiteit van de laser werd geobserveerd.

De belangrijkste maat volgend uit de fitting is
de parameter \( \mu \), dewelke de gemiddelde hoeveel-
hed foto-elektronen voorstelt geproduceerd

\(^2\)Wanneer een PMT daadwerkelijk een foton vangt wordt
er een foto-elektron gegenereerd dat vervolgens versterkt
wordt tot een detecteerbaar signaal.

\(^3\)De efficiëntie van een detector is berekend gebruik
makend van een Poisson distributie met \( \lambda = 1.79 \). De kans
dat er geen foto-elektronen gegenereerd worden, P(0), is
dan 17%, leidend tot een 83% efficiënte detector.
per trigger. Dit is bijgevolg een maat voor de efficiëntie van de meting.

Figuur 2: Gefitte PMT respons aan het ladingspectrum van een PMT belicht door een laser.

De volledige trigger bestaat uit een rij van 8 scintillatoren boven en onder de opstelling, individueel uitgelezen door een time-to-digital module. Wanneer twee scintillatoren getriggerd worden, bekomt men een schatting van de richting van het voorbijkomende muon. Figuur 3 toont de hoekdistributie van de gevange muonen, dicht aanleunend tegen de verwachte cosinus-kwadraat distributie. De distributie is echter verschoven over 5.73°, waarschijnlijk het gevolg van de bovenste rij die niet perfect boven de onderste rij ligt.

Figuur 3: Cosinus-kwadraat gefit aan de hoekdistributie van de gedetecteerde muonen.

Tabel I: \( \mu \) voor de gefitte resultaten.

<table>
<thead>
<tr>
<th>WLS</th>
<th>geen WLS</th>
<th>WLS</th>
<th>geen WLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>full</td>
<td>0.0761</td>
<td>leeg</td>
<td>0.0003625</td>
</tr>
<tr>
<td>vol</td>
<td>0.02249</td>
<td>leeg</td>
<td>0.000004</td>
</tr>
<tr>
<td>leeg</td>
<td>0.01083</td>
<td></td>
<td>0.003025</td>
</tr>
<tr>
<td></td>
<td>±0.0006</td>
<td></td>
<td>±0.00003</td>
</tr>
<tr>
<td></td>
<td>±0.0002</td>
<td></td>
<td>±0.00003</td>
</tr>
</tbody>
</table>

VI. SAMENVATTING VAN DE METEERESULTATEN

Alvorens de uiteindelijke metingen uit te voeren is er bevestigd dat het gevangen licht werkelijk Cherenkov straling is. Identieke metingen zowel in een volle als in een lege tank uitgevoerd tonen aan dat het gemiddeld aantal foto-elektronen \( \mu \) gevange in de volle tank enkele honderden keren hoger is dan in de lege. Aangezien de simulatie reeds aantoont dat 80-90% van het licht in de tank afkomstig is van Cherenkov straling is daarmee de afkomst van het signaal bevestigd. Uiteindelijke metingen werden uitgevoerd op een volle tank met en zonder WLS, zowel voor een volle als een lege tank. Uitgaande van de simulatie wordt een hogere \( \mu \) verwacht voor de metingen met WLS alsook voor de metingen in een volle tank. De gefitte waarde voor \( \mu \) worden getoond in tabel I en vertonen de verwachte trends. De gesimuleerde waarde voor \( \mu \) blijkt steeds een factor 23 tot 33 hoger te liggen, vermoedelijk veroorzaakt door verliezen in de opstelling niet in rekening gebracht in de simulatie (zoals refractie aan het oppervlak van de WLS en PMT).

Een verdere analyse van de metingen wordt uitgevoerd door het selecteren van de events in dewelke zowel in de bovenste als in de onderste triggers een signaal werd teruggevonden. Deze eis goot vermoedelijk de events weg die getriggerd werden door ruis of waarbij het muon in de tank werd geabsorbeerd of de tank zijdelings verliet. Dit zou bijgevolg leiden naar een verhoging van \( \mu \), dit werd echter niet teruggevonden. Een mogelijke verklaring is gebaseerd op de veronderstelling dat elk trigger signaal ondubbelzinnig veroorzaakt werd door een muon, noise triggers e.d. worden dus genegeerd. Het gebrek aan correlatie kan dan gewijt worden aan het falen van de onderste trigger om het muon te detecteren. De maat voor dit falen is de trigger efficiëntie.

Gebaseerd op de gemaakte veronderstelling kan de trigger efficiëntie van elk van de onderste trigger scintillatoren berekend worden. Voor elk trigger signaal van de bovenste rij zal een muon
ofwel door een van de onderste scintillatoren gaan ofwel de tank zijdelings verlaten, de verhouding daarvan werd berekend op basis van de simulatie. Door vervolgens te kijken naar het aantal gedetecteerde muonen in elk van de onderste scintillatoren tegenover het verwachte aantal muonen kan de efficiëntie berekend worden. Per berekening wordt slechts één scintillator boven en onder gebruikt zodat de berekening acht keer herhaald kan worden per onderste scintillator. Figuur 4 toont de resultaten. In tegenstelling tot de verwachte vlakke curve werd een cosinusachtige afhankelijkheid van de hoek tussen bovenste en onderste scintillator teruggevonden. Dit is mogelijk het gevolg van anisotropie in de scintillator efficiëntie (eventueel veroorzaakt door de langere padlengte) of een fout in de berekening maar kon niet meteen rechtgezet worden.

![Figuur 4: Berekening van de efficiëntie van de onderste scintillatoren geplot tegen de hoek met de bovenste scintillator, gebruikt voor de berekening.](image)

**VII. Conclusies**

Er werd aangetoond dat het mogelijk is Cherenkov licht op te vangen met gebruik van een WLS en de simulatie toonde dat dit veel potentiële vertoont. Voornamelijk de vrijheid in geometrie laat toe efficiënt licht te vangen, compenserend voor de kleine vangstprobabiliteit van de WLS. Verder werd door het individueel uitlezen van de trigger scintillatoren een meer gedetailleerde interpretatie van de metingen verkregen die toelaat een aantal foute veronderstellingen te verwerpen.

**Referenties**

Bibliography

[38] IceCube Collaboration. *The Detection of Neutrinos in IceCube*.


[51] Saint-Gobain Crystals.


[56] Roithner. STAR405F5 data sheet.


