

STUDY OF PROTOTYPE DETECTOR FOR UHE ν_τ DETECTION

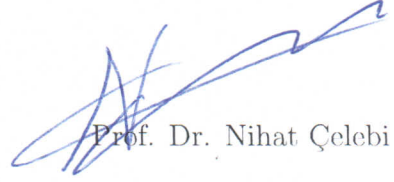
by

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THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE ABANT İZZET BAYSAL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF PHYSICS

JANUARY 2011

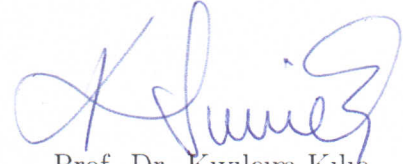
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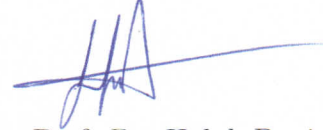
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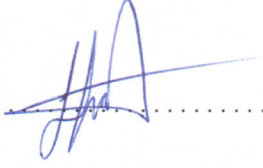


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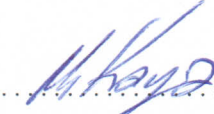
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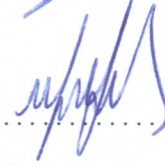
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To My Family . . .

ACKNOWLEDGEMENTS

I am heartily thankful to my advisor, Haluk Denizli, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. I would like to express the deepest appreciation to my supervisor, Maurizio Iori, whose patience and kindness, as well as his academic experience, have been invaluable to me.

I am deeply indebted to the Research assistants, Ferdi Altıntaş, Sevgi Altıntaş, Akın Sağırılı, Gürcan Yıldırım and Atılğan Altıncök for their friendship.

A special thanks is to Asaf Tolga Ülgen for his friendship, patience and his help when i produce the some graphics of this thesis.

I would like to thank my friends, colleagues and teachers in physics department for their friendship and encouragement all trough my years at AIBU.

I would like to thank the INFN for financial aid and i also thank to Scientific Research Projects Unit (BAP) for supporting this work under the grant number: BAP - 2009.03.02.324, by Abant Izzet Baysal University.

I would like to express my gratitude to the director of the International Foundation High Altitude Research Stations Jungfrauoch and Gornergrat, Prof. Erwin Flückiger and Dr. Fabio Ferrarotto for his invaluable help while developing the DAQ program.

I am thankful to my family, for their support, patience, understanding and financial support...

ABSTRACT

STUDY OF PROTOTYPE DETECTOR FOR UHE ν_τ DETECTION

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Master of Science, Department of Physics

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January 2011, 112 pages

Cosmic ray showers are originated in the upper atmosphere by the energetic protons and other particles from outer space. The showers mainly consist of hadronic (pions, muons, etc. . .) and electromagnetic (electrons, positrons, photons, etc. . .) components with different energies and moving in different directions. It is a very important scientific issue to detect these showering particles at Earth's surface. Moreover, subjects such as the measurement of these particles on very-large scales, the studies on cosmic muon flux and its affects on our electronics systems are also important issues.

In addition, the preliminary test results of the prototype detector, working at Sphinx Observatory Center-Jungfrauoch (3600 m a.s.l.)-Switzerland is presented in this thesis. This prototype detector is designed to measure a large angles cosmic rays emerging from the Earth crust. This station provides us an opportunity to understand if the prototype detector works safely (or not), under hard environmental conditions (average air pressure is about 653.3 mbar, and the air temperature is changing between $-37^\circ C$ and $+10^\circ C$). The station consist

of two towers includes four scintillation counters. The new electronics systems (i.e., DRS4 Board, Trigger Board) and the data acquisition software programs have been also tested. In addition, particle identification capability of the prototype have been simulated with GEANT4 program based on Monte Carlo package. This kind of detector will be part of a large area (several square kilometer) surface array designed to measure Ultra High Energy (UHE) (0.01-100 EeV) neutrinos by using the Earth Skimming strategy. The prototype detector is capable of discriminating the direction of the particles (up/down) by using Time of Flight technique.

The results presented in this thesis is the first attempt to carry out the analysis of the 38.083 days (914 hours) data with a new setup.

Keywords: Cosmic Rays, Flux Measurement, Ground Based Detector, Astroparticle Physics Instrumentation

ÖZET

ÇOK YÜKSEK ENERJİLİ ν_τ BULUNMASI İÇİN PROTATİP DEDEKTÖR ÇALIŞMASI

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Ocak 2011, 112 sayfa

Kozmik ışın duşları (showers), dış uzaydan gelen enerjik protonlar ve diğer parçacıkların üst atmosferde etkileşmesiyle oluşurlar. Duşlar çoğunlukla farklı enerjilerde ve farklı yönlerde hareket eden hadronik (pionlar, müonlar, vb.) ve elektromanyetik (elektronlar, pozitronlar, fotonlar, vb.) bileşenlerden oluşurlar. Dünya yüzeyinde bu duş parçacıklarının belirlenmesi çok önemli bir bilimsel konudur. Üstelik bu parçacıkların çok yüksek oranlarda ölçümü, kozmik müon akı ve elektronik sistemler üzerindeki etkileri üzerine yapılan çalışmalarda önemli konulardır.

Bu tezde, dünyanın kabuğundan geniş bir açıyla gelen kozmik ışınları ölçmek için tasarlanmış olan ve denizden 3600 m yükseklikte İsviçre Jungfrauoch'ta bulunan Sphinx Gözlemevinde çalışmakta olan prototip dedektörün ilk test sonuçları sunulmuştur. Bu protatip dedektör dünyanın kabuğundan geniş bir açıyla yayılan kozmik ışınları ölçmek için tasarlanmıştır. Bu istasyon, ortalama basıncın 653.3 mbar olduğu ve hava sıcaklığının $-37^{\circ}C$ ile $+10^{\circ}C$ arasında değiştiği zorlu çevre

koşulları altında prototip dedektörün güvenli bir şekilde çalışıp çalışmadığını anlamamız için bir fırsat sağlamaktadır. İstasyon iki kuleden oluşan dört tane sin-tilasyon sayacını içermektedir. Yeni elektronik sistemler (örneğin; DRS4 Board, Trigger Board) ve veri toplama yazılım programları da test edilmiştir. Buna ek olarak, prototip dedektörün parçacık tanımlama yeteneği Monte Carlo tabanlı Geant4 simulasyon programı kullanılarak simule edilmiştir. Bu tür dedektör, “Earth Skimming” stratejisini kullanarak çok yüksek enerjili (0.01-100 EeV) tau nötrinolarını ölçmek için tasarlanan geniş yüzey alanına (birkaç kilometre kare) sahip dedektör dizinin bir parçası olacaktır. Protatip dedektör uçuş zamanı (Time of Flight) tekniğini kullanarak parçacıkların yönünü (yukarı/aşağı) ayırt edebilme yeteneğine sahiptir.

Bu tezde sunulan sonuçlar yeni bir kurulumla alınan 38.083 günlük (914 saatlik) veri analizinin ilk denemesidir.

Anahtar Kelimeler: Kozmik Işınlr, Akı Ölçümü, Zemin Tabanlı Dedektörler, Astroparçacık Fizik Enstrümantasyon

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CHAPTER 1

INTRODUCTION

The Cosmic Rays (CRs) are mainly high energy protons and heavier nuclei accelerated by astrophysical Galactic and extra-Galactic objects. Although they come directly from the astrophysical objects of interest, it is impossible to point back to their source position in the sky because they are deflected from the galactic and extragalactic magnetic fields. Also neutral cosmic messengers have some limitations: neutrons decay after they travel relatively long distances, while γ -ray photons have a limited travel due to their interactions with the electromagnetic background light.

In this scenario, neutrinos seem to be very interesting particles in order to study astrophysical phenomena: they do not suffer deflection from magnetic fields because they are neutral, they are stable particles and they interact only weakly.

The scintillation detector prototype is composed of 4 scintillation tiles. The detection principle is based on the reconstruction of the muonic neutrino (ν_μ) track direction using the light emitted by charged-particles, created by neutrino interaction. Muons produced by charge-current interactions are important because of they are the charged leptons with longest range in the atmosphere. In addition muons retain almost the same direction of their parent neutrinos.

The aim of this thesis is the measurement of the cosmic ray coming from at large zenith angle as a function of the zenith angle. This detector prototype will be part of a large area (several square kilometer) surface array designed to measure Ultra High Energy (UHE) (0.01-100 EeV) neutrinos by using the Earth Skimming strategy.

The experimental data of the detector prototype is analyzed. The measure-

ment of the cosmic ray flux, performed by a reconstruction algorithm. In order to improve the purity of the analyzed data, some cuts was performed on the reconstructed events.

The thesis is organized in the following way.

- In chapter 1 an introduction to the physics of the CRs is given and Neutrino astronomy is then given briefly. Some potential astrophysical sources of high energy muonic neutrinos are presented. The physics of neutrinos and detection principle is explained.
- Chapter 2 contains the description of atmospheric muons and production of the secondary particles is described briefly. Skimming strategy is then explained.
- In chapter 3 a description of the detector prototype and a brief explanation of the detector layout is given. The components of the detector prototype are explained.
- Chapter 4 the Monte Carlo simulations of the particle identification strategy is studied.
- In chapter 5 the data acquisition system, coincidence and time of flight methods are described. Flux calculation and optimization parameters are then given. Finally daq and filter programs are explained briefly.
- Chapter 6 describes the final results of the detector prototype and of the cosmic ray flux at 88° incident angle are presented.

1.1 High Energy Neutrino Astronomy

The weakly interacting nature of neutrino and its neutral electric charge make this particle the cosmic messenger on which the astrophysics efforts will focus. Its small interaction probability combined with the expected fluxes, require the use of a very large volume detector and long operation times.

In this chapter a brief introduction to the physics of the CRs is given and some potential astrophysical sources of high energy neutrinos are then discussed. In the next the physics of neutrinos and the detection principle of neutrino is briefly described.

1.2 Cosmic Rays

The existence of cosmic rays (CRs) has been known since 1912 when Victor Hess took an electro-meter (a device for measuring the presence of charge) to a high altitude in a hot air balloon. Contrary to what was expected, the electro-meter discharged more quickly at higher altitudes, leading Hess to conclude that the source of the discharge must be from above the atmosphere rather than the Earth itself [1].

The primary cosmic radiation which consists predominantly of protons, alpha particles and heavier nuclei is influenced by the galactic, the interplanetary, the magneto-spheric and the geomagnetic magnetic fields while approaching the Earth. The energy spectrum of cosmic radiation extends over 11 orders of magnitudes (from 1 up to 10^{11} GeV), and its shape is described by a simple power law

$$\frac{dN_p}{dE} = K \cdot E^{-\gamma} \quad (cm^{-2}s^{-1}sr^{-1})$$
$$F(E) \propto E^{-\gamma} \tag{1.1}$$

where the flux F of particles with energy E and γ is the spectral index of the flux

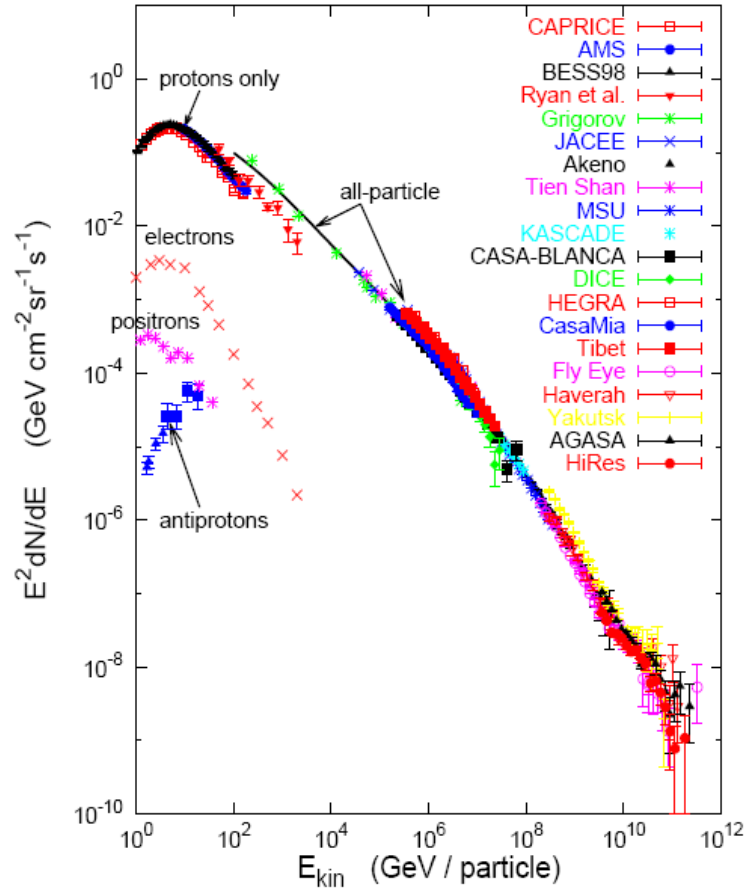


Figure 1.1: The flux spectrum of cosmic rays from air shower measurements, from [2]. The range of the direct detection is shown on low-energy domain.

spectrum. The flux of primary particles changes from $\approx 1000 \text{ m}^{-2} \text{ s}^{-1}$, at $E \approx 10^9 \text{ eV}$, to $1 \text{ km}^{-2} \text{ century}^{-1}$ at the highest energies. Thus the detection techniques are so different. The CRs spectrum can be directly detected by using Stratospheric balloons or satellites based experiments for $E < 10^{14} \text{ eV}$ and the flux of primary particles becomes so low at higher energies, above 10^{14} eV . At these energies, more extensive ground based detectors are necessary for getting a significant statistics.

Figure 1.2 shows the CRs flux measured from different experiments at Earth. The measured power-law spectrum of CRs (eq. 1.1) has an index $\gamma = 2.7$ up to $3 \cdot 10^{15} \text{ eV}$. Above that energy there is a variation is referred to as the *knee*. The responsible mechanism for the acceleration of particles to higher energy is

the *Fermi mechanism* [4, 5]. It explains the acceleration of the particles by oscillation back and forth between the two sides of a shock wave. Supernova remnants (SNRs) are the most accredited site of the acceleration for CRs up to knee region [6].

At the energy about $4 \cdot 10^{18}$ eV, the spectral index of the power-law is flattening which is referred to as *ankle* of the CR spectrum. The spectral index of the power-law spectrum decreases from 3.1 to 2.75 at the ankle region. The ankle may be caused by the transition from a galactic to an extragalactic origin of the cosmic ray particles [7]. The region of Ultra High Energy Cosmic Ray (UHECR) spectrum about 10^{19} eV, there is a cut-off, called GZK cut-off which was predicted by Greisen, V. Zatsepin & Kuzmin [8, 9] independently imposes a theoretical upper limit on the energy of cosmic ray from distant source. Above energies of $5 \cdot 10^{19}$ eV the center-of-mass energy exceeds the energy threshold for photo-pion production and pair-production. UHE particles, are extragalactic origin ($\gtrsim 50$ Mpc (*megaparsec*)) lose their energy in these processes till their energy has fallen below the threshold energy. Protons interact with the Cosmic Microwave Background radiation (CMB) and lose their energy by the process shown below

$$\gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0 \quad (1.2)$$

The γ_{CMB} photons with their $2.7^\circ K$ temperature fill up the universe as background radiation which was measured by Penzias & Wilson [10] as an excess in the antenna temperature at 4080 Mc/s. This GZK cut-off is very important for astrophysicians because of that limits the existent UHECRs emitters to our local super-cluster of galaxies.

1.3 High Energy Photons and Neutrinos

Charged particles (e^- , p , ...) are not good information carriers because of they are affected by galactic and extragalactic magnetic fields so they are not point back their source position in the universe. Hence we need a probe which is electrically neutral particles. Best candidates currently known to exist are the photons and neutrinos. The neutral particles are supposed to be the products of charged particles and they are not accelerated by any acceleration mechanisms. Due to the fact that photons have many advantages as cosmic messenger:

They are copiously produced, stable, neutral, and easy to detect over a wide energy range, they have some disadvantages as the properties of the astrophysical energy sources, Active Galactic Nuclei (AGN) and the hot, dense regions which form the central engines of stars are not investigated by directly. Furthermore, higher energy photons cannot deliver information from a source at the edge of own galaxy because it will annihilate into an electron pair in an encounter with $2.7^\circ K$ microwave photon before reaching us. This is known as the GZK-cut-off which suppresses any possibility of surveying the sky over distances greater than 100 Mpc (*megaparsec*) with high energy (>10 TeV) gamma rays [11]. Particles are mainly accelerated by astrophysical objects using the two main models are called *leptonic* and *hadronic*. When electrons are accelerated the leptonic model is referred and when protons at the other nuclei are accelerated, the hadronic model is referred. Neutrinos are produced only in hadronic acceleration despite the high energy photons are produced both in hadronic and in leptonic (Inverse Compton process) models. Accelerated protons will interact in the surroundings of the CRs emitters with photons predominantly via the Δ^+ resonance:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n \quad (1.3)$$

Also, the protons will interact with surrounding (protons, neutrons and nuclei), giving rise to the production of neutral and charged mesons. The relationship between the source of γ -ray and neutrinos is the meson-decay channel. Neutral mesons decay in two photons via the process

$$\pi^0 \rightarrow \gamma + \gamma \quad (1.4)$$

while charged mesons decay in muons and their neutrinos via the process shown below

$$\begin{aligned} \pi^+ &\rightarrow \nu_\mu + \mu^+ \\ &\hookrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ \pi^- &\rightarrow \bar{\nu}_\mu + \mu^- \\ &\hookrightarrow \nu_\mu + \bar{\nu}_e + e^- \end{aligned} \quad (1.5)$$

Due to the mechanism that produce CRs which can produce also high energy photons and neutrinos (eq. 1.4 & 1.5). Candidates for neutrino sources are in general also γ -ray sources. Thus the γ -ray measurements give a crucial information about primary cosmic rays and put the constrain to expected neutrino flux. This connection between neutrinos, γ -rays and cosmic rays put upper limits on the expected neutrino flux from extragalactic sources. Since the neutrino energy generation rate will never exceed the generation rate of high energy protons.

1.4 Gamma Rays

As a consequence of different processes, were occurring in the universe, would result in γ -ray emission. These processes included cosmic ray interactions with interstellar gas, interactions of energetic electrons with magnetic fields and su-

pernova explosions. Because of the fact that the gamma rays are not affected by the galactic magnetic fields, they are good information carriers. During the past decades, several γ -ray detectors were developed. Space-based detectors are extending their energy range from GeV to TeV with AMS and GLAST, while all ground-based Cerenkov experiments aim at lower threshold, and better angular resolution. So one can choose one of the way to reach these aims by using:

- larger field of view, better pointing and energy measurements using multiple telescopes (VERITAS [12], HEGRA [13] and HESS [14]).
- better, or rather, ultimate imaging with 17m MAGIC mirror [15].
- larger mirror area.

The most important experiment using the atmospheric Cerenkov technique is The Millagro experiment. Because the idea of the Milagro is to lower the threshold of conventional air shower arrays to TeV energy by instrumenting a million gallons of ultra-pure water with photomultipliers for time-varying signals the threshold may be even lowers such as bursts [11]. Because of high energy γ -rays, above 10 GeV, interact with infra-red, microwave and radio background photons and that processes are limit the mean free path (m.f.p.) traveled by photons. In figure 1.4 represents this effect in absorption length versus their energy.

Especially, above 10 TeV the horizon of photons is limited to less than 10 Mpc, is much less than the horizon of UHECRs. Consequently, there is only one candidate to carry the information about the extreme regions of the Universe, neutrinos, and the possible sources of neutrino will be discussed in next section.

1.5 Sources of Galactic Neutrinos

Neutrinos are the best messenger for locating the source of cosmic rays, because of being electrically neutral and stable so they are not deflected in the *Galactic*

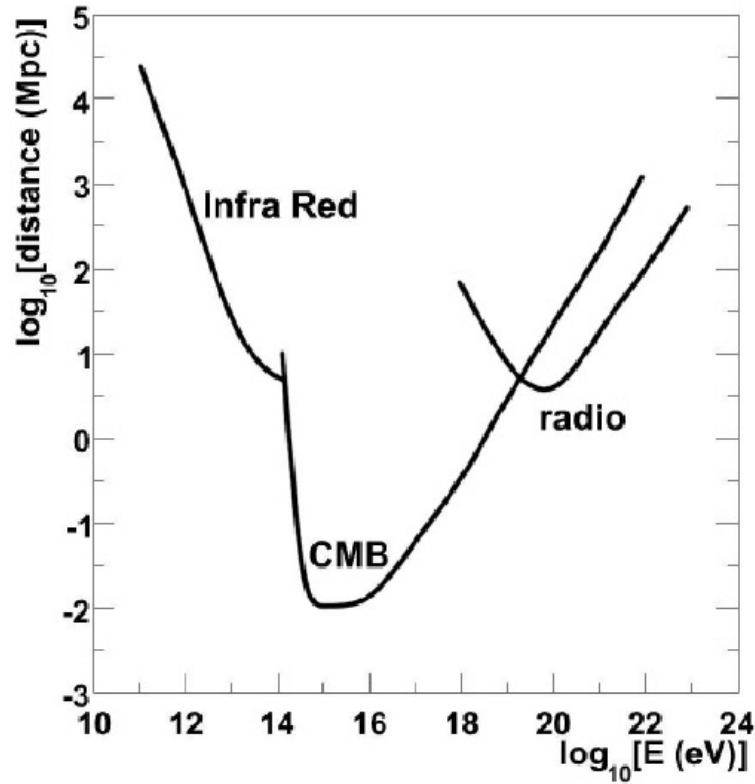


Figure 1.2: Absorption length of photons as a function of their energy

and *extra-Galactic* magnetic fields. The advantage of galactic sources, like *supernova remnants (SNRs)*, *pulsar-wind nebulae (PWNe)* and *micro-quasars* are thought to accelerate particles at least up to energies of $3 \cdot 10^{15}$ eV, also called the *knee* region of the cosmic ray spectrum, is relatively close to the Earth (~ 10 kpc) with respect to extra-galactic sources like *γ -ray bursts*, *active galactic nuclei (AGN)* and *starburst or neutrino factory*. In the following, most promising galactic sources are presented.

1.5.1 Supernova Remnants(SNRs)

Supernovas are now generally considered to be the best candidates for the sources of some galactic cosmic ray particles. All stars above an original mass of more than 8 solar mass ($\sim 2 \cdot 10^{30}$ kg) are expected to explode at the end of their lifetime, when a massive star collapses, the outer parts of the star explode at speeds

of up to 10000 kilometers per second and the observable effect of such an explosion is called a *supernova*.

The ejected matter expands at supersonic velocities, driving a strong shock into the surrounding medium. At this shock wave, particles accelerated by the Fermi mechanism and gain additional energy due to its strong magnetic fields. Because the cosmic rays eventually escape the supernova remnant, they can only be accelerated up to a certain maximum energy ($\sim 10^{15}$ eV) which depends upon the size of the acceleration region and the magnetic field strength.

1.5.2 Pulsar Wind Nebulae (PWNe)

Pulsars are known to power winds of relativistic particles that can produce bright nebulae by interacting with surrounding medium and pulsar's own magnetic field. These pulsar winds blows-out jets of very fast-moving material into the nebula. A synchrotron origin of these emission is suggested by the optical, X-ray and radio experiments. Gamma ray emission from the Vela PWN, is around TeV region, has detected by HESS telescope [14] claiming that this emission is produced by the inverse Compton mechanism. To understand the possibility of the observed TeV-gamma rays (like as the Crab, the Vela PWN), with the consequent flux of neutrinos, needs a kilometer-scale neutrino telescope.

1.5.3 Microquasars

Microquasars are galactic X-ray binary systems, consist of a compact object (a black hole or a neutron star and companion star). Mass transfer of microquasar from the companion to the compact object through the formation of an accretion disc and the presence of the jets makes them similar to small quasars. Both of them exhibit jets of relativistic matter ejected perpendicularly to both sides of an accretion disc. The jets contain relativistic electrons that produce the synchrotron radiation detected at radio wavelengths. The best candidates as neutrino sources

are the steady microquasars SS-443 and GX-339-4 [16].

1.6 Sources of Extra-Galactic Neutrinos

The energy spectrum of CRs above the *ankle*, is dominated by extra-galactic sources. The UHECR flux sets an upper limit to the extra-galactic high energy neutrino intensity. The upper limit known as the Waxman-Bachal limit [17, 18] are needed to detect the expected diffuse extra-galactic flux in the energy range of ~ 1 TeV to ~ 1 PeV [19].

The best candidate sources of UHECR are *Active Galactic Nuclei* (AGN) and *Gamma Ray Bursts* (GRBs) are also the most likely to be detectable neutrino sources. In order to determine the extra-galactic neutrino sources, one may needs to construct km-scale neutrino telescope. There is also another method to prove the existence of extra-galactic neutrino sources is trough the measurement of the *cumulative flux* in the whole sky. Since there is no directional information, the only way to detect this *diffuse flux of high energy neutrinos* is looking for an excess of high energy events in the energy spectrum over the background of the atmospheric neutrinos (produced by interactions of CRs with the Earth's atmosphere).

1.6.1 Active Galactic Nuclei (AGN)

As known brightest sources in the universe are *Active Galactic Nuclei* (AGN). All of the active galactic nucleus have a super-massive black hole at their center. Since the black hole spinning it into a rapidly rotating accretion disk, the materials inside the accretion disk is heated to intensively high energies, and this extremely high-energy radiation and matter are finally ejected trough their rotational axis of the disk in jets which expands far into space.

When an active galactic nuclei is the same direction with the observer, that

appears very bright which is called *blazar*. Because of that provides observable fluxes of neutrinos from TeV to EeV energies, blazars are thought to be the sources of the highest energy cosmic rays [11].

1.6.2 Gamma Ray Bursts (GRBs)

Gamma-ray bursts (GRBs) are short and very bright flashes of MeV γ -rays, lasting from milliseconds to several minutes, although a typical burst lasts a few seconds. Subsequent to the initial γ -ray bursts (known as *afterglow* of the GRB) produce X-ray, optical and radio emission. One of the proposed models for the origin of GRBs with duration of tens of seconds (known as *long bursts*) is the collapse of massive stars, supernova to a black hole [20, 21].

Although the internal mechanisms of generating GRB has not been well understood yet, it is assumed that the *relativistic fireball* model is leading to produce it. In this model, a fireball expanding with a high relativistic velocity (Lorentz factor $\Gamma \sim 10^{2.5}$) is produced in the collapse, powered by radiation pressure. GRB detection has an advantage that is practically background free, since the neutrino events (the same process of eq. 1.3) are coincident both in direction and time with gamma rays. GRBs may prove to be excellent source of neutrinos with energies from MeV to EeV and above.

1.7 Neutrino Oscillations

Neutrino oscillations are well-known phenomenon that will be affect the cosmic neutrino flux on Earth. One may try to derive the neutrino oscillations probability function following this section. Mostly the weak eigenstates are written as a

coherent linear superposition of the mass eigenstates:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad (1.6)$$

where ν_e , ν_μ and ν_τ flavor eigenstates, they are linear combinations of mass eigenstates ν_1 , ν_2 and ν_3 . U represents the *unitary* matrix (known as lepton mixing matrix).

The investigation of neutrino oscillations is going on by considering the case of two generation mixing, e.g.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} \quad (1.7)$$

where the mixing matrix has only one free parameter which is a mixing angle, θ , and the flavor and mass eigenstates are related by

$$|\nu_e\rangle = +|\nu_1\rangle \cos \theta + |\nu_2\rangle \sin \theta \quad (1.8)$$

$$|\nu_\mu\rangle = -|\nu_1\rangle \sin \theta + |\nu_2\rangle \cos \theta \quad (1.9)$$

lets write the mass eigenstates in terms of the weak eigenstates

$$|\nu_1\rangle = +|\nu_e\rangle \cos \theta - |\nu_\mu\rangle \sin \theta \quad (1.10)$$

$$|\nu_2\rangle = +|\nu_e\rangle \sin \theta + |\nu_\mu\rangle \cos \theta \quad (1.11)$$

Now we can write the wave-function, Ψ , of an electron-neutrino, ν_e , at time $t = 0$, supposing an ν_e with momentum $\mathbf{p}$ is produced in a nuclear beta-decay, and

$$\Psi_{(t=0)} = |\nu_e\rangle = |\nu_1\rangle \cos \theta + |\nu_2\rangle \sin \theta \quad (1.12)$$

where a neutrino of momentum $\mathbf{p}$ is referred by the states $|\nu_i\rangle$. The time-dependent parts of the wave function are

$$|\nu_1(t)\rangle = a_1(t) |\nu_1\rangle \quad (1.13)$$

$$|\nu_2(t)\rangle = a_2(t) |\nu_2\rangle \quad (1.14)$$

where $a_1(t) = e^{\frac{-iE_1t}{\hbar}}$ and $a_2(t) = e^{\frac{-iE_2t}{\hbar}}$. After a time t , the wave function is

$$\Psi_{(t)} = a_1(t) |\nu_1\rangle \cos \theta + a_2(t) |\nu_2\rangle \sin \theta \quad (1.15)$$

A phase difference between the two components is seen when the masses of ν_1 and ν_2 are not equal to each other. So this phenomena leads to pick up the components of the $|\nu_\mu\rangle$ states from the $|\nu_e\rangle$ state.

By implementing the expressions for $|\nu_1\rangle$ and $|\nu_2\rangle$ from equations 1.8 and 1.9 into the equation 1.15 gives

$$\Psi_t = \left[a_1(t) \cos^2 \theta + a_2(t) \sin^2 \theta \right] |\nu_e\rangle + \sin \theta \cos \theta \left[a_2(t) - a_1(t) \right] |\nu_\mu\rangle \quad (1.16)$$

When the state is observed a time t after the production, the probability of that is observed as a muon-neutrino, ν_μ , $P_{(\nu_e \rightarrow \nu_\mu)}$ which is given by

$$\begin{aligned} P_{(\nu_e \rightarrow \nu_\mu)} &= \langle \nu_\mu | \Psi_{tau} \rangle^2 \\ &= \left| \sin \theta \cos \theta [a_2(\tau) - a_1(\tau)] \right|^2 \\ &= \sin^2 2\theta \sin^2 \left[\frac{(E_2 - E_1)}{2\hbar} \tau \right] \end{aligned} \quad (1.17)$$

If $m \ll E$ then the equation 1.17 reduces to

$$P_{(\nu_e \rightarrow \nu_\mu)} = \sin^2 2\theta \sin^2 \left[\frac{(\Delta m^2 \tau)}{4E\hbar} \right] \quad (1.18)$$

where $\Delta m^2 = m_2^2 - m_1^2$. If the neutrinos are observed a distance L away the source, then $\tau = \frac{L}{c}$ and

$$P_{(\nu_e \rightarrow \nu_\mu)} = \sin^2 2\theta_{12} \sin^2 \left[\frac{(\Delta m_{12}^2 \tau)}{4E\hbar} \right] \quad (1.19)$$

the second neutrino oscillation is

$$P_{(\nu_\mu \rightarrow \nu_\tau)} = \sin^2 2\theta_{23} \sin^2 \left[\frac{(\Delta m_{23}^2 \tau)}{4E\hbar} \right] \quad (1.20)$$

where Δm^2 is measured in km and E is the neutrino energy in GeV . The probability of the oscillation depends on the *unknown* parameters θ and Δm^2 [22, 23].

Due to the interaction of UHECRs with atmosphere, mostly produced particles are pions (and other leptons). After a short time, this pions decay to gamma, muon and their neutrinos/antineutrinos. Subsequently produced muons also decay to electrons, positrons and their neutrinos/antineutrinos. Therefore, the neutrino fluxes of the different flavors are expected to be at the source in the ratio:

$$\nu_\mu : \nu_e : \nu_\tau = 2 : 1 : 0 \quad (1.21)$$

According to these neutrino oscillation parameters, the flux ratio of neutrinos from source (i.e. verily long baseline L) in changes to a flux ratio at Earth (observation level) as

$$\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1 \quad (1.22)$$

This result was proved in Super-Kamiokonde detector [24].

1.8 Neutrino Detection Principle

The most promising way of neutrino detection, because of very weak interaction, is to construct a huge volume/area of detectors and bury the detectors. There

are various techniques, classified in table 1.1.

Radiation	Medium	μ -Det	E_ν Thres.	Atten. Length	Spectral Region
Cerenkov	Filtered H ₂ O	Y	GeV	100 m	300-500 nm
	Polar Ice	Y	GeV	$\simeq 15$ -45 m	300-500 nm
	Deep Ocean	Y	GeV	$\simeq 40$ m	350-500 nm
	Natural Lake	Y	GeV	$\simeq 20$ m	400-500 nm
Ceren. Radio	Moon	N	> 500 EeV		1-2 GHz
	Polar Ice	N	> 5 GeV	$\simeq 1$ km	0.1-1 GHz
Acoustic	Salt	N	$> \text{PeV}$	?	10-50 kHz
	Ice	N	$> \text{PeV}$	?	10-30 kHz
	Water	N	$> 1 \text{ PeV}$	$\simeq 5$ km	10-20 kHz
	Air	N	$> \text{EeV}$	($\simeq 100$ km)	30-100 MHz
EAS Radar	Air	N	EeV	10 km	337 nm
N ₂ fluorescence	Air	N	EeV	10 km	337 nm
EAS particles	Air	N	10 PeV	1 km	100 MHz

Table 1.1: Proposed techniques for large neutrino detectors [25].

1.8.1 Neutrino Interactions

Neutrinos are weakly interacting particles. So they can interact with matter via the so called *neutral-current* (NC) interaction by exchanging the Z^0 boson.

$$\nu_l + N \rightarrow l + X \quad (1.23)$$

where N is the target nucleon and l is the flavor of neutrinos, or via the *charged-current* (CC) weak interaction by exchanging the $W^\pm$ bosons.

$$\nu_l + N \rightarrow l + X \quad (1.24)$$

In a neutral-current interactions, the neutrino transfers some of its momentum and energy to the target particles, then leaves the detector. The target particle may be accelerated to the relativistic speed when it is charged and sufficiently light. At the relativistic speed, accelerated particle emits light, which is known as *Cerenkov light*, is observed directly. Because of the contribution of all flavors of neutrino regardless of the neutrino energy, there is no any information about neutrino flavors after the interaction. But in a charged-current interactions, the

neutrino turn into the muon, electron or tau if the neutrino has enough energy to create their heavier lepton parts [26].

In this thesis, the briefly described method is used. Incident neutrinos turn into muons, electrons and taus inside a mountain by interacting with the atoms of target material (here it is rock), though the charged-current interaction depends on their flavor. If the neutrino flavor is electron so that electrons will decay quickly and produce a shower inside the target material. If it is muon means that will be travel a very long distance before decaying, thus it is not convenient to use for this method. However, the τ leptons are produced inside the mountain, have an enough lifetime to go out from mountain. When this particle goes out from mountain it will interact with the atoms of air so that will produce a shower in the air.

CHAPTER 2

PHYSICS OF ATMOSPHERIC MUONS

The atmospheric muons are the main topic of this thesis. This chapter contains the description of atmospheric muons and production of the secondary particles is described briefly. Skimming strategy is then explained.

2.1 Cosmic Rays in the Atmosphere

The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer. “*Primary*” cosmic rays are accelerated but astrophysical source and “*secondaries*” are produced in interaction of the primaries with atoms inside the atmosphere. The vertical fluxes of the major cosmic ray components in the atmosphere in the energy region where the particles are most numerous shown in Fig. 2.1.

All the particles are produced in interactions of the primary cosmic rays in the air except for protons and electrons near the top of the atmosphere. Muons and neutrinos are products of the decay of charged mesons (K and π), while electrons and photons originate in decays of neutral mesons, as for example:

$$\begin{aligned}\pi^+ &\rightarrow \nu_\mu + \mu^+ \\ \pi^- &\rightarrow \bar{\nu}_\mu + \mu^- \end{aligned} \tag{2.1}$$

These particles play an important role at ground based detector systems because of a great number of atmospheric muons reaches its active volume. As a consequence they represent the most abundant signal and they can be used to calibrate

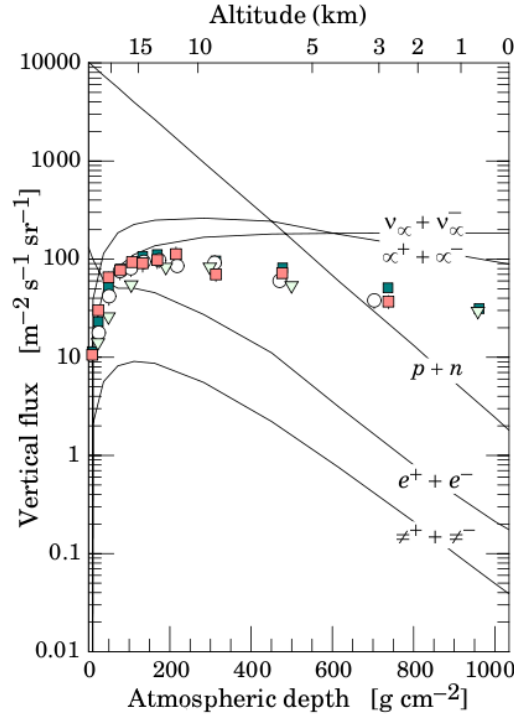


Figure 2.1: The vertical fluxes of cosmic rays in the atmosphere [27].

the detector and to check the validity of Monte Carlo simulation programs to the passage of charged particles. On the other hand atmospheric muons constitute the main background source for the neutrino detection.

Most of the measurements are made at ground level or near the top of the atmosphere, airplanes and balloons. These measurements shows that the most numerous charged particles are muons at ground level (see Fig. 2.1). Most of the muons are produced high in the atmosphere (≈ 15 km) and lose about 2 GeV to ionization before reaching the ground. Their energy and angular distribution reflect a convolution of production spectrum, energy loss in the atmosphere, and decay. For instance, 2.4 GeV muons have a decay length of 15 km, which is reduced to 8.7 km by energy loss. The mean energy of muons at the ground is ≈ 4 GeV. The energy spectrum is almost flat below 1 GeV, steepens gradually to reflect the primary spectrum in the 10 - 100 GeV range, and steepens further at higher energies because pions with $E_\pi > \epsilon_\pi \approx 115$ GeV tend to interact in the atmosphere before decay. The energy spectrum of atmospheric muons is

one power steeper than the primary spectrum. The integral intensity of vertical muons above 1 GeV/c at sea level is $\approx 70 m^{-2} s^{-1} sr^{-1}$ [28, 29].

Figure 2.2 shows the muon energy spectrum at sea level for two angles. At large angles low energy muons decay before reaching the surface and high energy pions decay before they interact, thus the average muon energy increases.

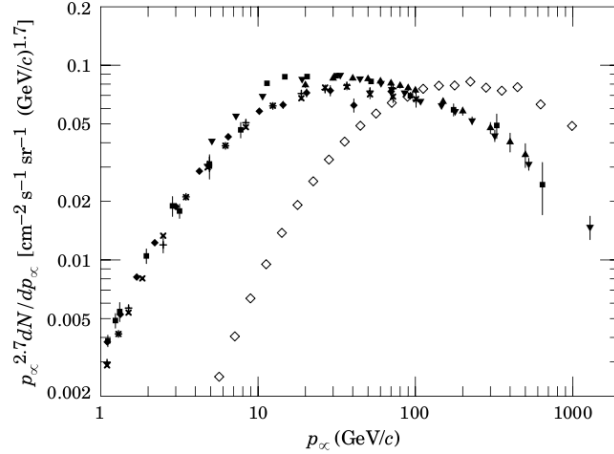


Figure 2.2: The spectrum of muons at $\theta = 0^\circ$ (filled signs), and the others for $\theta = 75^\circ$.

2.2 Secondary Particles and Decay of Secondaries

Cascade of Cosmic Rays

When high energy cosmic rays interact with atoms of the upper atmosphere, they produce cascades of *secondary* particles that shower down through the atmosphere to the earth's surface. Secondary cosmic rays include kaons and pions, which quickly decay and gamma ray interaction with atmospheric atoms. The downward particle flux increases with increasing atmospheric depth until reaching a maximum close to 100 g/cm^2 as shown in figure 2.1. Then it decreases due to the decays and atmospheric absorption. Most secondary particles reaching the earth's surface are muons, with an average intensity of about 100 per cm^2 per second [30]. Among the particles of the cascades due to primary cosmic rays, electron and muon neutrinos can be found. In simplified picture, the produc-

tion of atmospheric neutrinos may be described as a three step process. In the first step, the primary cosmic particles collide with atmospheric nuclei, thereby producing charge pions and kaons, either directly or via intermediate particles. In the second step, the decay of these charged mesons gives rise to part of the atmospheric ν_μ and $\bar{\nu}_\mu$ neutrino fluxes:

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad K^+ \rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \quad \text{and} \quad K^- \rightarrow \mu^- + \bar{\nu}_\mu\end{aligned}\tag{2.2}$$

In the third step, the muon decay, leading to ν_e and $\bar{\nu}_e$ fluxes as well as additional ν_μ and $\bar{\nu}_e$ fluxes:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu\tag{2.3}$$

However, table 2.1 shows, that other processes contribute to the neutrino fluxes which do not follow the simple 3-step picture.

π^+	$\rightarrow$	$\nu^+\nu_\mu$	(100%)
μ^+	$\rightarrow$	$e^+\nu^e\bar{\nu}_\mu$	(100%)
K^+	$\rightarrow$	$\nu^+\nu_\mu$	(63.5%)
	$\rightarrow$	$\pi^+\pi^0$	(21.2%)
	$\rightarrow$	$\pi^+\pi^+\pi^-$	(5.6%)
	$\rightarrow$	$\pi^0\mu^+\nu_\mu$	(3.2%) ($K_{3\nu\mu}$)
	$\rightarrow$	$\pi^0e^+\nu_e$	(4.8%) ($K_{3e\nu}$)
	$\rightarrow$	$\pi^+\pi^0\pi^0$	(1.73%)
K_s^0	$\rightarrow$	$\pi^+\pi^-$	(68.6%)
K_l^0	$\rightarrow$	$\pi^+\pi^-\pi^0$	(12.37%)
	$\rightarrow$	$\pi^\pm\mu^\mp\nu_\mu$	(27%) ($K_{3\nu\mu}$)
	$\rightarrow$	$\pi^\pm e^\mp\nu_e$	(38.6%) ($K_{3e\nu}$)

Table 2.1: Decays of μ , π and K which are mainly responsible for the production of neutrinos in the atmosphere. The decays of μ^- , π^- and K^- are charge conjugates of the decays above [31].

2.3 Skimming Strategy

The detection of very high energy cosmic neutrinos is important in view of exploring the astrophysical information about point sources, astrophysical accelerators and to study of neutrino oscillation effects on high energy fluxes of neutrino mixing. They have great potential as probes of astrophysics. They have escaped from regions of dense matter and point back to their sources in the universe. One can test for the existence of neutrino oscillations by looking for up-going showers from Earth-skimming tau neutrinos [37, 33]. The Earth-skimming neutrino strategy is the following that, as neutrinos go through the Earth they can undergo charged-current (CC) interactions close to their exit point below the surface of the Earth, which is shown in Fig. 2.3.

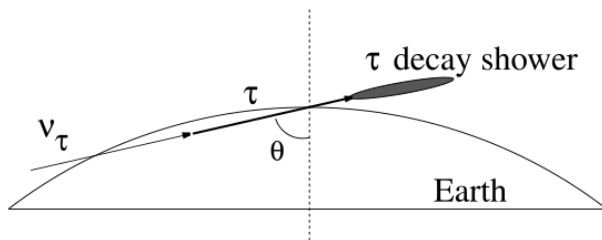


Figure 2.3: A schematic picture of Earth-skimming tau-neutrino events.

These interactions can produce extensive-air-showers under some circumstances that showers develop upwards in the atmosphere. Only those produced by ν_τ 's are of significance from the quantitative point of view, due to that lead to large detectable shower rates in the high-energy ranges of interests. This is because of the combined effect of the lepton lifetime, its energy loss and the neutrino cross-section. For ν_τ the mechanism can be described in three stages; the ν_τ enters the Earth and propagates through it, then it has a charged-current interaction just below the surface producing a τ that continues the propagation in matter with considerable energy loss and finally the τ exits the surface and decays in the atmosphere inducing an air shower.

The morphology of τ -air-shower would reflect the rich and structured behaviors of τ decay modes, UHE decay channels and the corresponding probability ratio as a shown in Table 2.2.

Decay	Secondaries	Probability	Air Shower
$\tau \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \dots$	μ^-	~ 17.4	Unobservable
$\tau \rightarrow e^- \bar{\nu}_e \nu_\tau \dots$	e^-	~ 17.8	One electromagnetic
$\tau \rightarrow \pi^- \nu_\tau \dots$	π^-	~ 11.8	One electromagnetic
$\tau \rightarrow \pi^- \pi^0 \nu_\tau \dots$	$\pi^-, \pi^0 \rightarrow 2\gamma$	~ 25.8	One hadronic, two electromagnetic
$\tau \rightarrow \pi^- 2\pi^0 \nu_\tau \dots$	$\pi^-, 2\pi^0 \rightarrow 4\gamma$	~ 10.79	One hadronic, four electromagnetic
$\tau \rightarrow \pi^- 3\pi^0 \nu_\tau \dots$	$\pi^-, 3\pi^0 \rightarrow 6\gamma$	~ 1.23	One hadronic, six electromagnetic
$\tau \rightarrow \pi^- \pi^- \pi^+ \nu_\tau \dots$	$2\pi^-, \pi^+$	~ 10	Three hadronic
$\tau \rightarrow \pi^- \pi^+ \pi^- \pi^0 \dots$	$2\pi^-, \pi^+ \pi^0 \rightarrow 2\gamma$	~ 5.18	Three hadronic, two electromagnetic

Table 2.2: τ Air-Shower Channels

This complex air shower mode would exhibit different interaction lengths in the air at 1 atm (~ 300 m for electromagnetic interaction length, 500 m for the hadronic interaction length, and 800 m for τ pions secondaries). Deep valleys such as the Grand Canyon, the famous Death Valley, or Whitney mountains in Nevada as well as glacial valleys in the Alps (where our prototype detector was installed at Jungfrau-Joch-Switzerland) have a great potential to observe UHE neutrinos by their contained horizontal showers in huge air volumes. The deep rock walls play the same role as the target beam dump for UHE neutrinos as well as filtering atmospheric cosmic rays. At the large depth ($\simeq 1$ km) and at horizontal angles ($\sim 60^\circ$) at energies above 1 PeV the atmospheric muon secondaries (crossing 2 km or more of rock matter) will be negligible, while a primary neutrino may interaction in the rock, leading to secondary leptons: one muon and tau tracks are long enough to emerge often from the mountain wall rock.

One of the estimation in Ref. [33] for τ horizontal showers are based on an interaction volume defined for an examples as follows: the Argentier Alps chain distance ($D \simeq 10$ km), the characteristic height (~ 1 km), the UHE $\nu_\tau - \tau$ energies (~ 3 PeV), the τ distance before decay ~ 150 m and the total interactive volume ($V \simeq 4.5 \text{ km}^3$, water equivalent). The expected total rate of $N_{ev} \sim 158$

event yr^{-1} at energies above 3 PeV in this valley. Wider angle acceptance (which is realistic) may lead to an order-of-magnitude increase in the detection rate at $E_\tau \sim 3 \text{ PeV}$.

$$N_{ev} = 158 \left(\frac{h}{1 \text{ km}} \right) \left(\frac{D}{10 \text{ km}} \right) \text{events yr}^{-1} \quad (2.4)$$

It is possible to extend to higher energies this estimation of general neutrino fluxes assuming a neutrino power law E^{-2} whose fluence scales linearly with present AGASA bounds ($3 \times 10^{13} \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) used for this estimate; [33, 35, 36, 37]

$$N_{ev} = 158 \left(\frac{h}{1 \text{ km}} \right) \left(\frac{D}{10 \text{ km}} \right) \left(\frac{E_\tau}{3 \text{ PeV}} \right)^{0.36} \text{events yr}^{-1} \quad (2.5)$$

CHAPTER 3

DESCRIPTION OF DETECTOR PROTOTYPE

The detector prototype, is based on two scintillator counters named *towers* are separated by 160 cm. Each counter includes one KURARAY organic scintillator and one low voltage H5783 Hamamutsu Photomultiplier Tube (PMT). The prototype detector, depicted in figure 3.1, is a multi-detector setup dedicated to measure the electromagnetic, muonic and hadronic components of the cosmic ray showers. It is located at High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG), Switzerland (at 3580 m above sea level, $7^{\circ} 59' 22''$ E, $46^{\circ} 32' 53''$ N).

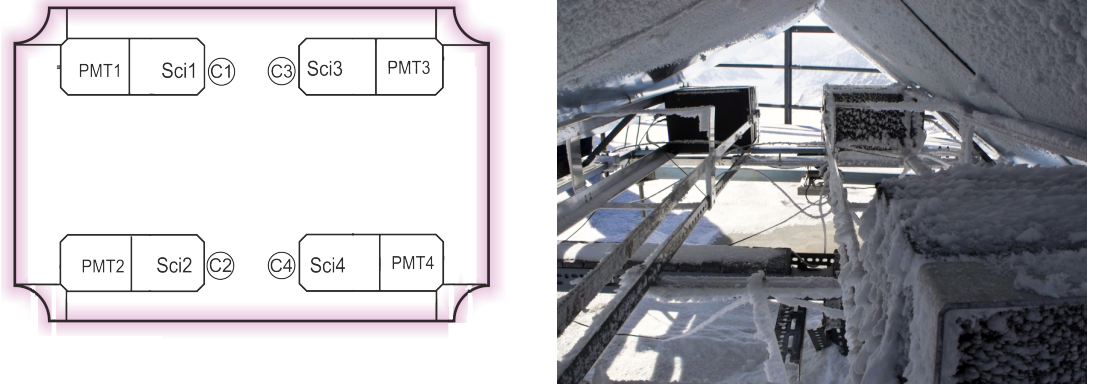


Figure 3.1: *Left:* Schematic top view of the detector prototype. The figure also shows the separation two tower stations *Right:* The detector prototype and its subsystems.

The main goal of this thesis is not only to measure the flux of cosmic rays at large zenith angle, emerging from the Earth crust but also to test new electronics and new Data Acquisition(*DAQ*) systems. Moreover, this research station provides us an opportunity to understand the performance of prototype detector under hard weather conditions such as the average air pressure around 653.3 mbar

and the air temperature between -37°C and $+10^{\circ}\text{C}$. Most of the experiments are focused on the vertical flux of cosmic ray showers going down from atmosphere or possible sideways toward the detection medium. Indeed the on-going experimental techniques use the timing information to obtain shower angular information, none of the present techniques uses the exact time information to discriminate the up-going or down-going particles by using Time of Flight (TOF) information. The prototype detector, is described in the next paragraph, is capable to separate these particles (up-going or down-going) by using TOF information.

The prototype detector station consists of two towers and each tower includes two counters separated by using 160 cm. Each counter has an organic scintillator ($20 \times 20 \text{ cm}^2$, 1.5 cm thick) wrapped with Tyvek paper and read by low voltage Hamamatsu H5783 photomultiplier tube. The station has four counters shown in figure 3.1. So it is easy to measure the cosmic ray flux by using these counters in the combination of C1-C2, C3-C4, C1-C4 or C3-C2. With some probability, a cosmic ray (generally muons) traversing the counter will cause a simultaneous pulse to occur in more than one detector, since with their high energy they will usually not stopped by a single counter. Thus we can use coincidence gating to count the cosmic rays by using timing information which is a way to distinguish these events from background radiation and photomultiplier noise.

Now we focus on detector components: scintillator, photomultiplier tube (PMT), trigger board and Domino Ring Sampler (DRS4) board.

3.1 Scintillators

Scintillators have the general property that they convert the energy deposited by ionizing radiation into light, usually in the near ultraviolet or blue region of the visible spectrum, later converted into an electric signal. In general, this signal provides us a variety of information such as sensitivity to energy, fast time response and pulse-shape discrimination.

A. Sensitivity to Energy:

Because of most scintillators have almost same linearity in the deposition of the energy means that the light output of the scintillator is directly proportional to the exciting energy. So the amplitude of the final collected signal is also proportional to the this energy.

B. Fast Response Time:

Because of having fast response and recovery time of scintillation detectors they can provide high precision timing information between two events so that leads to higher count rates.

C. Pulse-Shape Discrimination:

The technique known as *pulse-shape discrimination* is to distinguish between types of particles by analyzing the shape of the collected signal pulses.

At present, there are six types of scintillators but commonly used types are organic scintillators and inorganic crystals. The scintillation mechanism is different for all types. Since organic scintillator is used in our prototype, we briefly describe it.

3.1.1 Organic Scintillators

Organic scintillators are aromatic hydrocarbon compounds containing benzene cycle. Their most distinguishing property is a very rapid decay time on the order of a few nanoseconds or less.

3.1.1.1 Energy Levels in Organic Scintillators

The fluorescence mechanism in organic materials arises from transitions in the energy levels of a *single* molecule. Most of the practical organic scintillators are organic molecules which have symmetry properties associated with the electron structure. Energy from a charged particle is absorbed and excited states - the singlet states (spin = 0) are labeled S_1, S_2, S_3 and the triplet states are $T_1, T_2, T_3, \dots$

which are shown in figure 3.2.

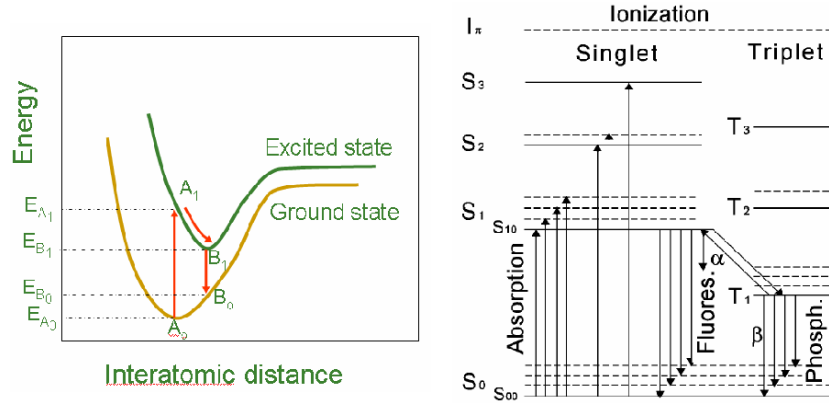


Figure 3.2: Energy levels of organic molecules.

The space between S_0 and S_1 is 3 to 4 eV for organic scintillators and this spacing is much smaller for upper states. Each of the S levels is subdivided into a series of fine structure (α) that corresponds to excited vibrational modes of the molecule. The typical spacing is 0.15 eV. The second subscript denotes the fine structure level. The spacing between S states is 3-4 eV and 0.15 eV in vibrational structure [38].

3.1.1.2 Scintillation Mechanism in Organic Scintillators

When scintillator materials, because of having the property known as *luminescence*, exposed to certain form of energy (light, radiation, heat etc...). They absorb and emit the energy in the visible light form. If this emission occurs immediately after absorption or within $10^{-8}s$ (atomic transition time), the process is usually called *fluorescence*. If it has a delay due to the excited state is metastable, the process is called *phosphorescence*. The scintillation mechanism in organic materials is the *fluorescence* mechanism, arises from transitions in the energy levels of a single molecule. Therefore the fluorescence can be observed independently of the physical state. Since the average energy is about 0.025 eV at room temperature all molecules are in the S_{00} state. When the charged particle passes through, kinetic energy is absorbed by the molecules, and electrons are

excited to the upper levels. The higher states S_2, S_3 , de-excite quickly ($\sim 10^{-12}$ s) to S_1 state through radiationless transitions (internal conversion). The states such as S_{11}, S_{12} that have extra vibrational energy and are not in thermal equilibrium with neighboring molecules, quickly lose energy. After in a short time (negligible) a population of excited molecules in S_{10} state is produced as the net effect of the excitation process. Scintillation light (prompt fluorescence) is emitted in transitions between S_{10} and ground state. The prompt fluorescence intensity at time t following excitation is described by

$$I = I_0 e^{\frac{-t}{\tau}} \quad (3.1)$$

where τ is the fluorescence decay time for the S_{10} level. In most organic scintillators, τ is the order of a few nanoseconds thus organic scintillators are *fast*. The lifetime for the T_1 is much longer than the S_1 state. T_1 is populated by a transition called an inter-systems crossing. The lifetime of the T_1 state can be ms. Transitions from T_1 to S_0 give rise to phosphorescence (delayed light emission). T_1 lies below S_0 , therefore the wavelength of the emitted phosphorescence is longer than the wavelength of the fluorescent light. The phosphorescent light can be discriminated from the scintillation light on the basis of timing and wavelength. The energy level diagram, shown in figure 3.2, explains why organic scintillators can be transparent to their own fluorescence emission. All fluorescence emissions (except $S_{10} \rightarrow S_{00}$) have a lower energy than the minimum required for absorption. There is a little overlap between emission and absorption spectra, therefore the emitted light mostly passes straight on through the scintillation medium. So while selecting a good scintillator detector one should pay attention the following requirements [40, 39, 38]:

1. high efficiency for conversion of exciting energy to fluorescent radiation
2. transparency to its fluorescent radiation to allow the light transmission.

3. a short time decay constant
4. emission in a spectral range consistent with the spectral response of existing photomultiplier.

In our prototype, we use KURARAY organic scintillators shown in figure 3.3. They have a dimension of $20\text{ cm} \times 20\text{ cm}$ with 1.5 cm thickness.



Figure 3.3: KURARAY organic scintillator $20 \times 20\text{ cm}^2$ and 1.5 cm thick.

Description	Light Output	Peak of Emission	Attenuation Length	Decay Time
SCSN-61	55% Anthracene	430 nm	0.92 m	2.5 ns

Table 3.1: Physical parameters of KURARAY SCSN-61 scintillator

Properties shown in table 3.1 are obtained with a sample which has a size of $1500\text{ mm} \times 50\text{ mm} \times 10\text{ mm}$. Emission spectra is shown in figure 3.4.

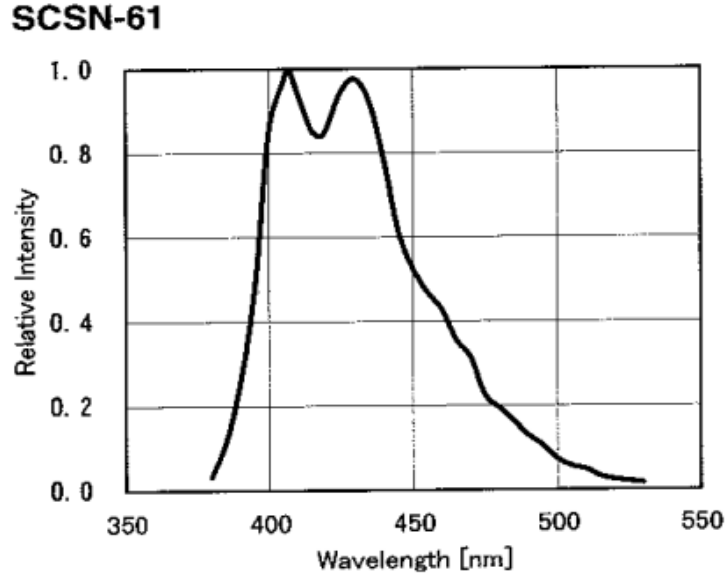


Figure 3.4: Emission spectrum of the KURARAY SCSN-61 scintillator.

3.2 Photomultiplier Tube (PMT)

Photomultiplier tubes (PMT's) are extremely good at converting light into an electrical signal; electrical pulses can be obtained from a few hundred visible photons. The scintillation light, produced inside the scintillator, is of low intensity, and has to be coupled to photomultiplier to amplify the electrical signal. A schematic diagram of a typical photomultiplier tube is given in figure 3.5.

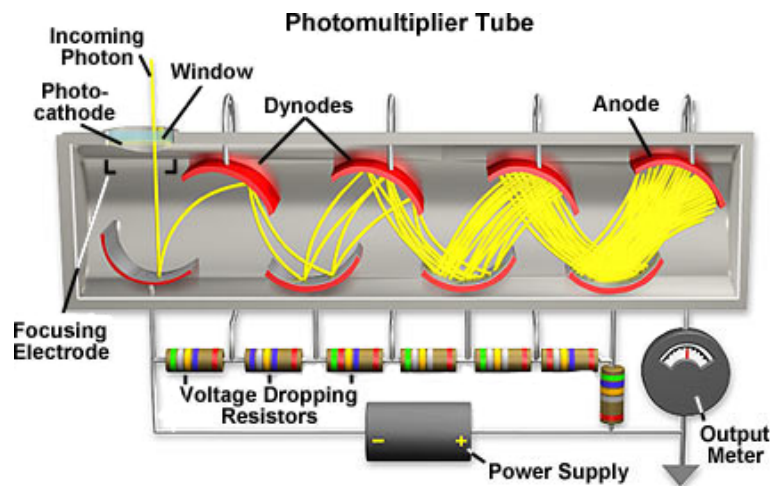


Figure 3.5: Schematic diagram of a photomultiplier tube.

The scintillation light (photons) is converted into photoelectrons via the pho-

photoelectric effect, the equation is

$$E = h\nu - \phi \quad (3.2)$$

where E is the kinetic energy of the emitted electron, ν is the frequency of the emitted electron, ϕ is the work function of the material. The efficiency for photoelectric conversion varies strongly with the frequency of the incident light and the structure of the material. This overall spectral response is expressed by the *quantum efficiency*,

$$QE_{(\lambda)} = \frac{\text{number of photoelectrons emitted}}{\text{number of photons incident on the photocathode}} \quad (3.3)$$

where λ is the wavelength of the incident light.

A set of metallic electrodes, are called *dynodes*, forms the electron multiplier section. The dynodes, set at progressively higher voltage, are located between the photocathode and the anode (see figure 3.5). A dynode re-emits electrons when struck by an electron. This emission of secondary electrons by a dynode, via the photoelectric effect [eq.3.2], is similar to photo electron emission by the photocathode. The electrons ejected from the photocathode are accelerated towards the first dynode due to the voltage differences between the photocathode and the first dynode, from which they knock out several electrons. These secondary electrons are accelerated, through the potential gradient between the first and second dynodes, towards the second dynode, where each of them ejects more electrons, and so on. The inter-dynode voltage permits the multiplication factor (called the *gain*, M ,) between the first stage of the n-dynode chain and the anode is

$$M = \delta_1 \delta_2 \delta_3 \dots \delta_i \quad (3.4)$$

where δ_i is the multiplication factor at the dynode i of the chain. If each electron produces about 4 secondary electrons when it strikes a dynode, 10^7 multiplication

factor can be achieved at the chain of 12 dynodes, and the charge collected at the anode for $M = 10^7$ is

$$\begin{aligned}
Q &= eM \\
&= 1.6 \times 10^{-19} C \times 10^7 \\
&= 1.6 \times 10^{-12} C \\
&= 1.6 pC
\end{aligned} \tag{3.5}$$

So the expected current at the anode within 5 ns is

$$i = \frac{dQ}{dt} = \frac{1.6 \times 10^{-12} C}{5 \times 10^{-9} s} = 0.32 mA \tag{3.6}$$

Generally, this current drives a 50Ω load: i.e., the photomultiplier is terminated with a 50Ω resistance. Then, a pulse of

$$\delta V = 0.32 mA \times 50 \Omega = 16 mV \tag{3.7}$$

is produced. Photomultipliers can be also characterized by a rise-time (typically ~ 2 ns). The rise-time is usually defined as the time needed for the output signal to increase from 10% to 90% of the maximal value. The time elapsed between the illumination of the photocathode and the signal at the anode is the *transit time* (typically ~ 30 ns), which can be understood as the time required for the electron to travel the length of the photomultiplier. The size of the pulse at the anode and the photocathode is proportional to the energy absorbed from the incident radiation by the scintillating material. Hence, the scintillation detector can be used to distinguish between different type of particles or incoming particles of the different type of the emitted light pulse. This pulse can be controlled by the dominant decay time of the scintillator and the electron transit time [41].

H5783 model photomultiplier tube, is produced by Hamamatsu company, deliver

high gain, wide dynamic range and high-speed response while counting the photons. It includes also its own high voltage generator is called Cockcroft-Walton high voltage generator. Table 3.3 summarized the specification of the Hamamatsu H5783 photomultipliers.

Parameter	Value	Unit
Input Voltage	+11.5 to +15.5	V
Max. Input Current	+9	mA
Max. Output Current	100	μ A
Effective Area	$\phi 8$	mm
Peak Sensitivity Wavelength	400	nm
Rise Time (at control voltage=0.8 V)	0.78	ns
Dark Current Typical (Max.)	0.2 (2.0)	nA
Gain (at control voltage=0.8 V)	$7.5 \times 10^5 - 1.0 \times 10^6$	
Weight	80	gr

Table 3.2: Specifications of Hamamatsu H5783 photomultiplier.

One can also see the characteristics such as cathode radiant sensitivity and gain of this model PMT in figure 3.6;

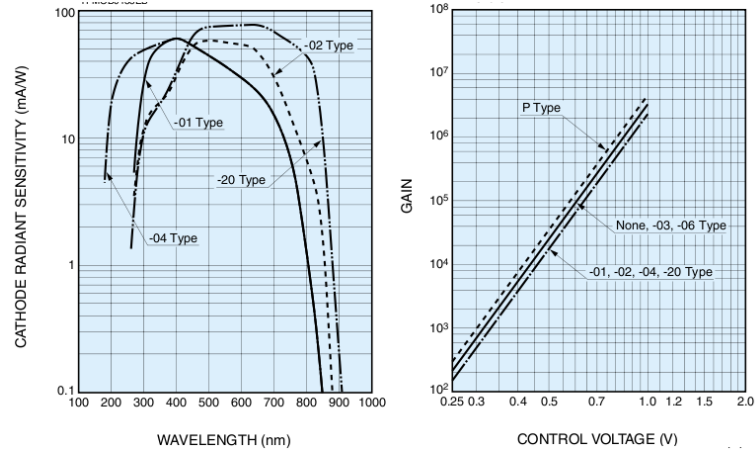


Figure 3.6: Characteristics of Hamamatsu H5783 photomultiplier.

3.3 Trigger Board

The Trigger Board, shown in figure 3.7, has been designed at University of Rome “La Sapienza”, Italy by Prof. Maurizio Iori and Giacomo Chiodi. It is a low

consumption board powered by USB port (+5.0 V). A Max1673 provides a regulated negative output from a positive input at up to 125 mA. The input range is 2 V to 5.5 V. The features of Max1673 charge-pump inverter is shown in Table 3.3. The dimension is 7 cm $\times$ 12 cm, on layer. 4 Lemo 00 inputs and 2 Lemo 00 outputs (one TTL and one NIM).

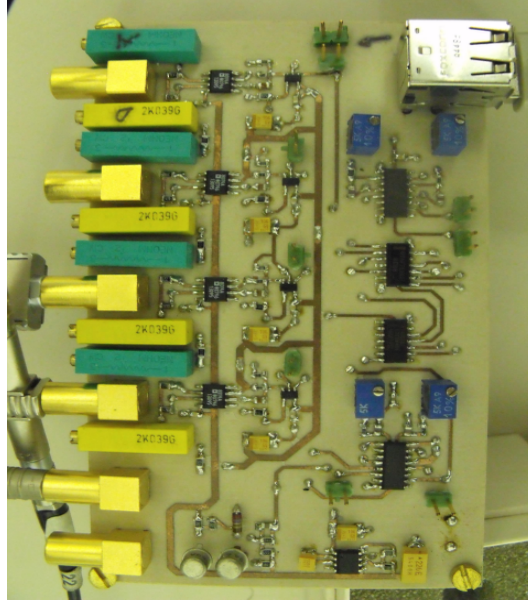


Figure 3.7: Trigger Board developed by M. Iori and G. Chiodi.

Parameter	MIN	TYP	MAX	Unit
Input Voltage Range	2.0		5.5	V
Min.Output Voltage	-1.5			mA
Max. Output Current	125			mA
Output Voltage	-2.90	-3.02	-3.15	V
Operating Temperature	$-40^{\circ}C$ to $+85^{\circ}C$			

Table 3.3: Characteristics of Max1673 charge-pump inverter [42].

3.3.1 Description of The Board Operation

Each amplifier receives the signal from one of 4 channels which has also a noise coming from the photomultiplier tube, i.e., a few mV. Each PM outputs has a sharp (~ 50 ns) pulse which is amplified by the low level preamplifier. The

preamplifier amplifies only sharp signals, making the detector units insensitive to light leakage.

The circuit, drawn schematically in figure 3.8 is based on the choice of the AD8014 8 pin SOIC package of Amplifier which offers a gain about 2 at 240 MHz bandwidth, low noise.

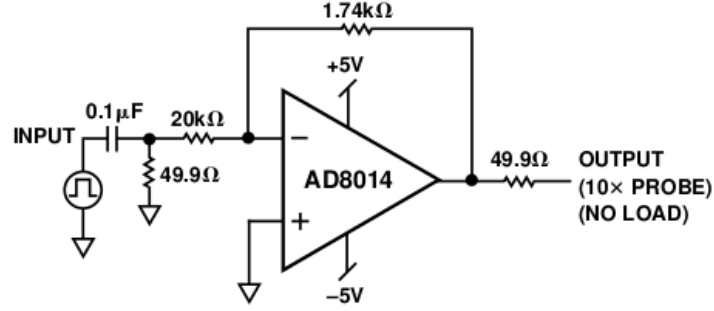


Figure 3.8: AD8014 as a Photodiode Preamplifier.

The produced pulse shape is shown in figure 3.9.

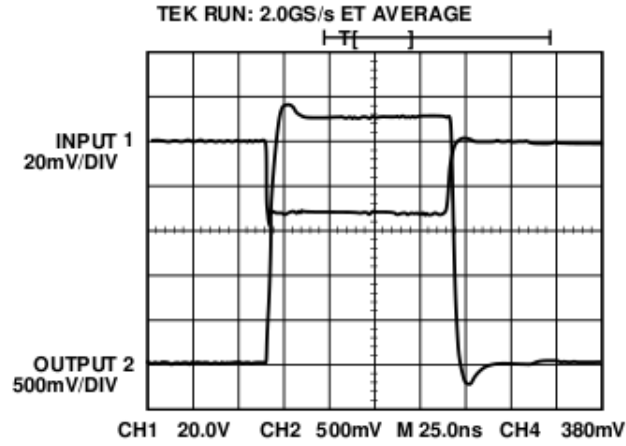


Figure 3.9: Pulse Shape.

The amplification can be adjusted by $2\text{ k}\Omega$ variable resistor (green) shown in figure 3.7. The features of AD8014 preamplifier are given in the table 3.4.

Now we need to turn the analog signals into digital ones, and we also need to eliminate very small signals, mostly caused by amplifier noise. Both goals are accomplished by using a comparator, which compares the amplified PMT signal

Parameter
* Low Power 1.15 mA (Max) for 5 V supply
* High Speed $\rightarrow 400\text{MHz}, -3\text{dB Bandwidth } (G = +1)$ $\rightarrow 4000\text{V}/\mu\text{s Slew Rate}$
* Fast Settling Time of 24 ns
* Operates on +4.5 V to 12.0 V supplies
* Very low noise $\rightarrow 3.5\text{nV}/\sqrt{\text{Hz}}$ and $5\text{pA}/\sqrt{\text{Hz}}$ $\rightarrow 5\text{nV}/\sqrt{\text{Hz}}$ Total Input Referred Noise at $G = +3$ w/ 500Ω

Table 3.4: Characteristics of AD8014 preamplifier [43].

to an adjustable threshold voltage. The amplified signal is inverted and sent to the LMV7219 Comparator with Rail-to-Rail output. The LMV7219 is a low-power, high speed comparator with internal hysteresis. The LMV7219 operating voltage ranges from 2.7 V to 5.0 V with push / pull rail-to-rail output. This device achieves a 7 ns propagation delay while consuming only 1.1 mA of supply current at 5 V. A $2\text{ k}\Omega$ resistor (yellow), shown in figure 3.7, tunes the threshold. The features of LMV7219 comparator are in the following table;

Parameter
* Low supply current : 1.1 mA
* Input common mode voltage range extends 200 mV below the ground
* Propagation delay : 7 ns
* Fast rise and fall time : 1.3 ns
* Ideal for 2.7 V and 5 V single supply applications
* Internal hysteresis ensures clean switching

Table 3.5: Characteristics of LMV7219 high-speed comparator [44].

Most high-speed comparators oscillate when the voltage of one of the inputs is close to or equal to the voltage on the other input due to the noise. Because of LMV7219 have 7 mV internal hysteresis to counter parasitic effects and noise. The internal hysteresis creates two trip points, one for the rising input voltage and one for the falling input voltage (shown in figure 3.10).

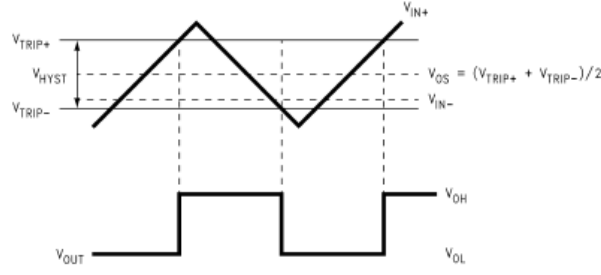
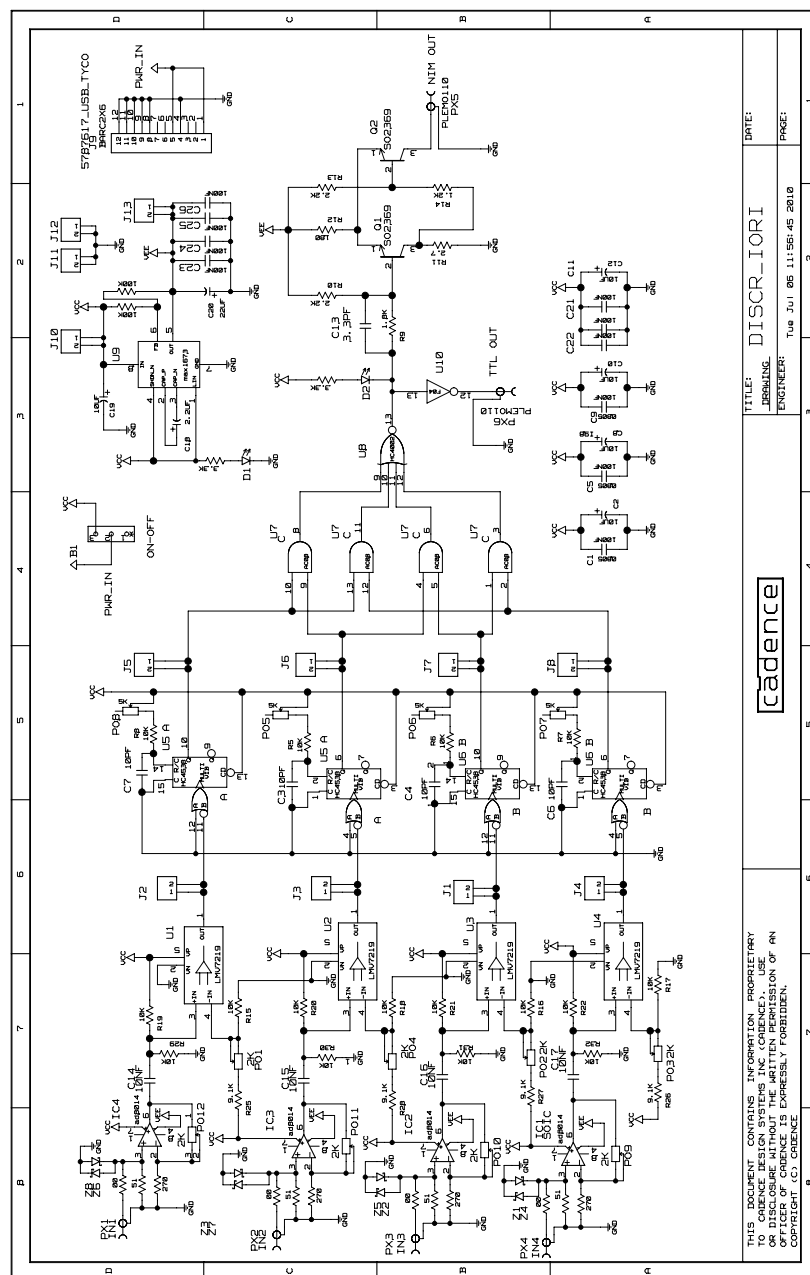


Figure 3.10: Input and output waveforms, non-inverting input varied.

When the comparator's input voltages are equal, the hysteresis effectively causes one comparator input voltage to move quickly past the other, thus taking the input out of the region where oscillation occurs with internal hysteresis. Because the pulses from the comparator are very short in time, we stretched the trigger output signal in time by a monostable multi-vibrator HCT4538. The trigger output (TTL and NIM) is now input for AND and OR gates. These four input devices (is shown in figure 3.11) allows the formation of coincident signal output from two of combinations; (1 AND 2) OR (3 AND 4) OR (4 AND 1) OR (2 AND 3).

Figure 3.11 shows printed circuit of the electronic components for four input channels. The discriminator, described above, on the board converts the voltage output from the preamplifier into a TTL pulse which can be used by the digital logic in the coincidence unit. If the signal from the preamplifier is above a set threshold voltage (which is adjusted using a potentiometer), the discriminator will output a +5 V signal, otherwise it will output 0 V.

The coincidence unit (comparator) takes the TTL signal output from the discriminator and stretch it (~ 100 ns). The two pulses from each scintillator are then fed into a binary AND, with a rising edge indication that a cosmic particle was detected. If the binary AND outputs High for one of the detectors, this is counted as a coincident event for that detector, meaning that the cosmic particle that passed through the detector.



3.4 Domino Ring Sampler Board

3.4.1 *Switched Capacitor Array Chip*

Flash ADC technique is commonly used for sampling and converting ultra-fast signals. Switched Capacitor Array (SCA) is used as a circular buffer that can sample continuously the signal until stopped by an external trigger. Once the last cell is written, it overwrites the first one. The array records the past information in the $N-1$ cells. This causes to a delay in the sampling period and the array depth, which is 120 ns for a 128-cell array at 1 GHz sampling rate. This rate controlled by an external clock at the sampling rate divided by the array depth. The first concept of a SCA was the Domino Sampling Chip (DSC), a fast analog memory produced in CMOS technology in 1989 [45].

In the case of the detector prototype the new data acquisition system is based on an ultra-fast analog-sampler, the Domino Ring Sampler version 4 (DRS4), with a frequency from 1 GSamples/s to 5 GSamples/s, and high resolution digitizers, 11 bits. The DRS4 is a SCA chip for fast waveform sampling of photomultiplier developed at Paul Scherrer Institute, Villigen Switzerland by Stefan Ritt. It is capable of digitizing nine channels at sampling speed up to 5 GSPS. It has SMA connectors for four input channels, each with 1024 capacitive sampling cells. Waveform digitizing takes place with an on-chip generated frequency ranging from 0.5 GHz to 5 GHz.

3.4.2 *The Domino Ring Sampler chip version 4*

The Domino Ring Sampler consist of an on-chip inverter chain generating a sampling frequency up to 5 GHz (domino wave circuit), eliminating the need to feed an external sampling clock in the GHz range into the chip. This signal opens a series of writing switches in all 8 sampling channels, where the single-ended input signal is sampled by low value (200 fF) capacitors. After being started, the domino wave runs continuously in a circular fashion until it is de-coupled from the write switches by a trigger signal, which freezes the current stored in

the sampling capacitors. The signal is then readout via a read shift register for external digitizers. A schematic view of DRS4 is shown in figure 3.12.

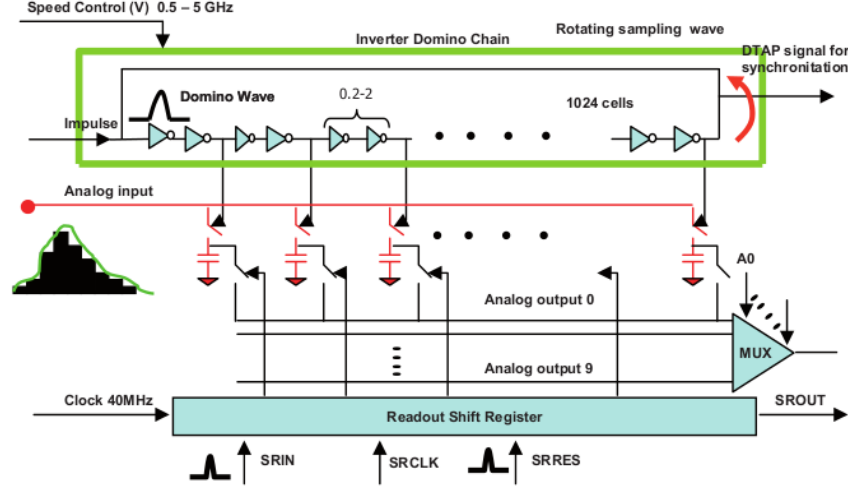


Figure 3.12: Schematic drawing of DRS4 chip.

3.4.3 The Domino Wave Circuit

The domino wave circuit is basically a series of 1024 double inverters. After raising the DENABLE signal high, a wave traverses through these inverters producing the write signal for sampling cells. Figure 3.13 shows a simplified schematic of three double inverter blocks. The first inverter is actually an AND gate. This allows to enable and to stop the domino wave at any time via the DENABLE. The domino wave runs continuously until it is stopped by a trigger signal that forces the DENABLE low, disabling the WRITE signal and freezing the current stored in the signal in the sampling capacitor.

The DRS4 board has some features, is powered with +5 V by USB port, and 50 Ω terminated TTL compatible input is implemented (LEMO 00 connector) for trigger purposes. An on-board discriminator with programmable level allows for self triggering on any of the four input channels. Figure 3.14 shows all components and final version of the DRS4 board [46, 47, 48].

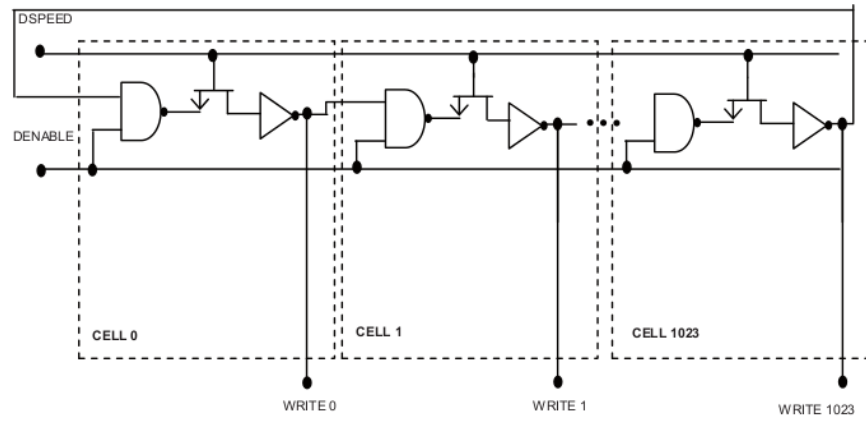


Figure 3.13: Simplified schematics of three out of 1024 double inverter blocks forming the domino wave circuit.

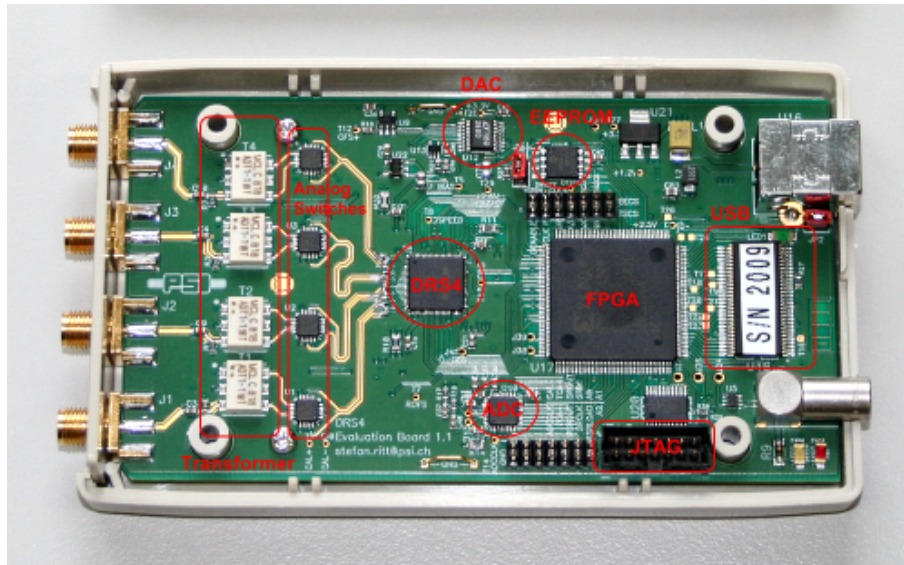


Figure 3.14: Picture of the DRS4 Evaluation Board with different components.

CHAPTER 4

SIMULATION OF DETECTOR PROTOTYPE BY GEANT4 PACKAGE

In order to understand the particle detection and identification capability of the prototype detector due to various physical interaction of incoming particles with the detection medium (i.e., scintillators), a simple program was written. The number of light photons reached to the photomultiplier tube (PMT) against light (or energy) is an important characteristics of scintillators, which can be obtained either experimentally or by Monte Carlo computations, via the calculation of energy deposited within the detector or by applying Monte Carlo code systems such as GEANT4 [49].

4.1 GEANT4

GEANT4 (for **GE**ometry **ANd** **T**racking) is a toolkit for the simulation of particle transport and interaction with matter, which uses object-oriented C++ as the programming language. GEANT4 lets the user make a selection model of particle interactions relevant for the simulation scenario. The features namely; the description of geometries of arbitrary complexity, standard electromagnetic processes (photons, electrons, positrons and muons). The processes can be assigned to particles, and models to processes, until all relevant interactions for all relevant particles in a simulation have been defined. The object oriented technology for event data persistency and data analysis was handled through PAW, HepRep [50].

The improved simulation program which simulates the interaction of primary

particles with the atoms of scintillator, air and lead absorber. The simulation takes place in a box, the *world volume*, which contains two scintillator tiles, one lead block and filled with air. The dimensions of scintillator tiles are $20 \times 20 \text{ cm}^2$, 1.5 cm thick and 160 cm apart. Figure 4.1 shows the two different detector setup.

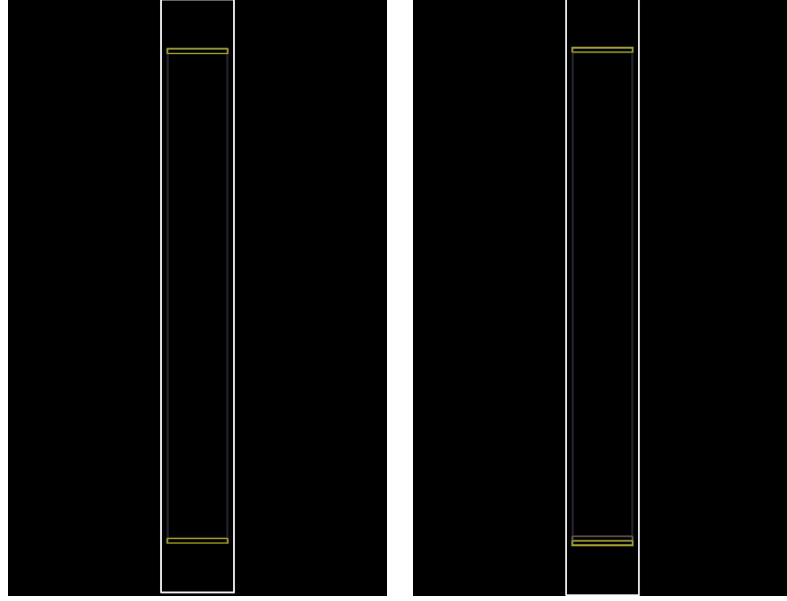


Figure 4.1: *Left:* Simulated view of the detector prototype *without lead absorber*. The scintillator tiles are $20 \times 20 \text{ cm}^2$, 1.5 cm thick and 160 cm apart. *Right:* Simulated view of the detector prototype *with 1.5 cm lead absorber* inserted before the bottom tile.

4.2 e^-/μ Identification Strategy

One can separate electron (or gamma) from muon by using the pulse height ratio of the two tiles in a tower, which gives along with the e/μ identification likelihood as a function of the pulse height ratio to separate e/γ from μ . Figure 4.2 shows the signal shapes of two PMT signals of same tower displayed by DRS4 Evolution Board.

So if one apply the following particle selection criteria:

- a *muon* has only a *sharp, singly-peaked signal* in both tiles

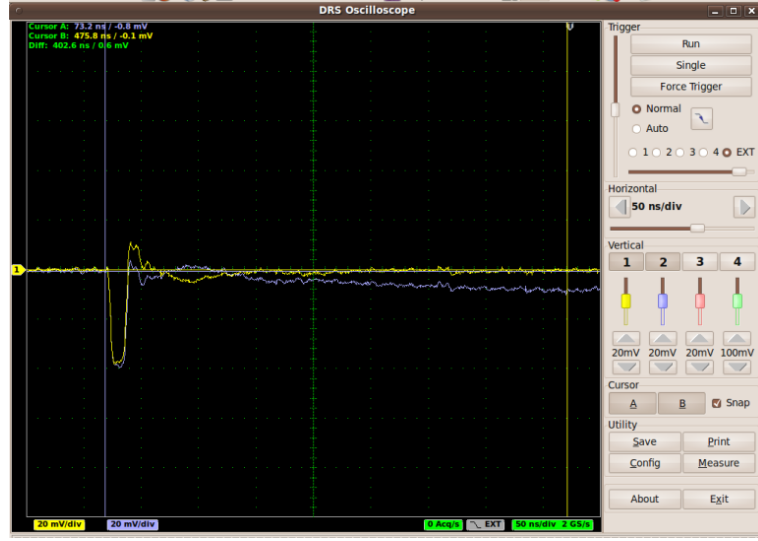


Figure 4.2: Two photomultiplier signals of same tower displayed by DRS4 Evolution Board. The units are mV (vertical axis) and ns (horizontal axis).

- while an *electron (or gamma)* has *multiple signal peaks in bottom tile*. It has also a *larger pulse height in the bottom tile*.

The best way to discriminate μ and $e(\text{or } \gamma)$ is to compare the *ratio of charge deposited in the bottom tile to top tile*, $R = \frac{q_B}{q_T}$, the *ratio of charge deposited in the top tile to bottom tile*, $R^* = \frac{q_T}{q_B}$. The expected two ratios R and R^* are *one* for muon and *greater than one* for electron (or gamma) for a given track.

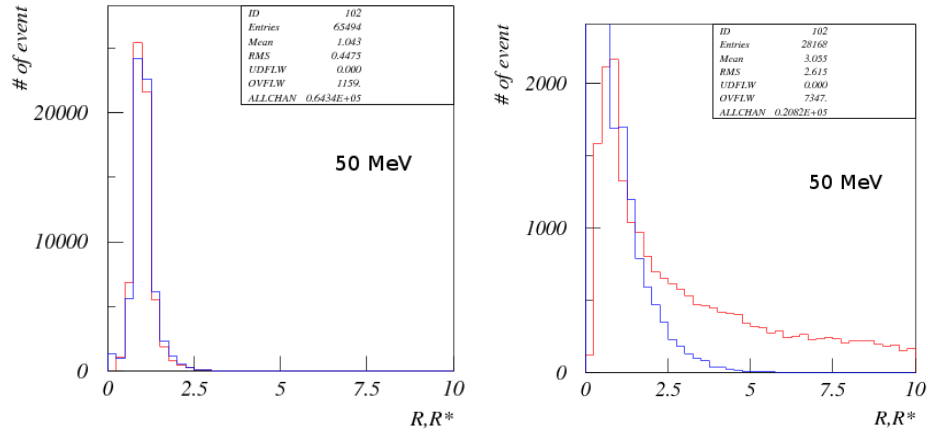
4.3 Simulation Studies

The simulation studies were done by using the geometries shown in figure 4.1. The primary electrons / gammas or muons with fixed kinetic energies (50, 100, 150 and 200 MeV) are created just outside the top scintillator tile. They fly into the top scintillator tile and interact with the air and with the atoms of lead absorber / the atom of the bottom scintillator tile. The simulated tracks all secondary particles until they stop or escape the world volume. The simulation was run for 100k electrons, 100k gammas, and 100k muons.

4.3.1 *Simulation of electrons without / with lead absorber for different energies*

In this part, the simulated detector prototype is composed of two scintillator tiles which have the dimensions of $20 \times 20 \text{ cm}^2$, with 1.5 cm thickness and 160 cm apart, and the primary particles are electron with different energies (50, 100, 150 and 200 MeV) are used (figure 4.1).

While the particles are passing through the matter, they lose energy in the matter due to the interactions leading one of the physical processes such as Ionization, Bremsstrahlung, Photoelectric, Pair-production, Compton or Inverse Compton scattering. Figure 4.3 represents the ratios, R (blue), R^* (red), of total energy (charge) deposited in scintillators for different energies. In the left side of the figure 4.3 shows the results are produced without lead absorber and in the right side of the figure shows the results which are produced with lead absorber.



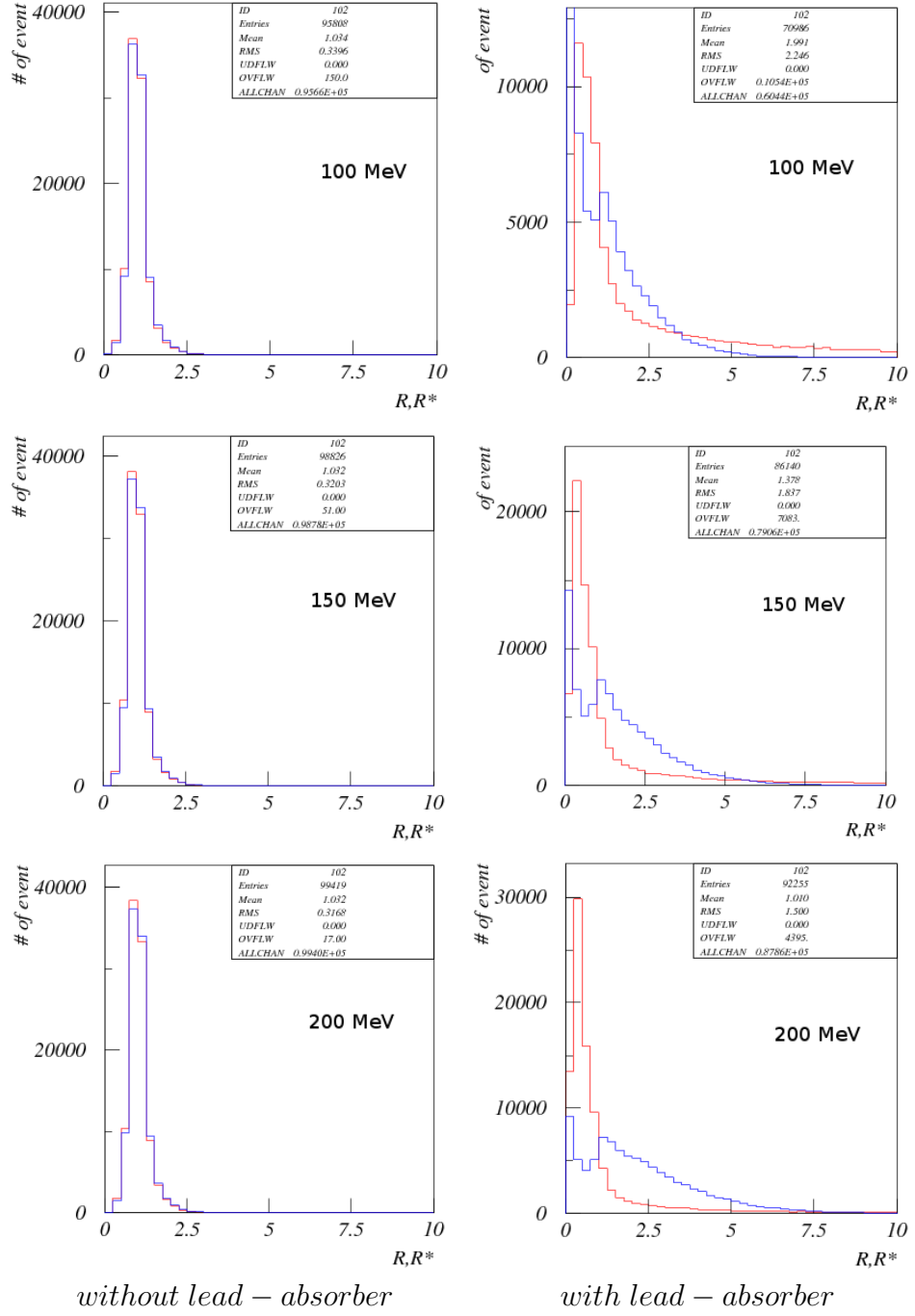
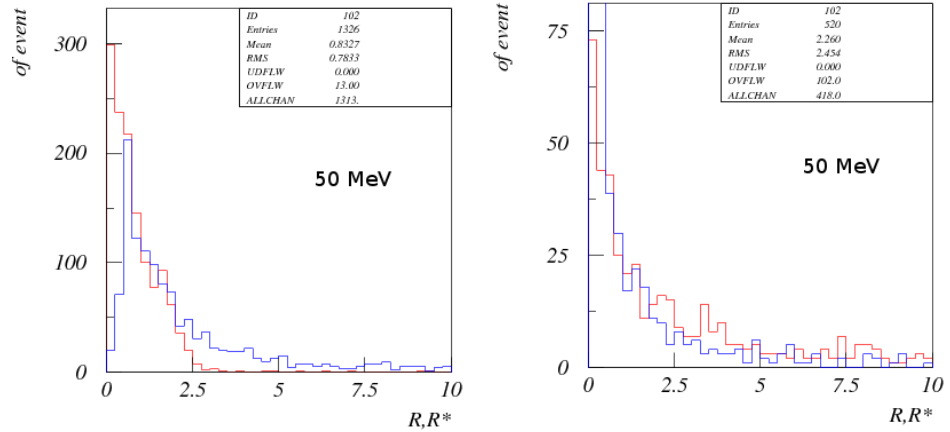


Figure 4.3: These plots, created by using 100k *electron* with 50, 100, 150 and 200 MeV energies, represent the ratios R (blue), R^* (red). The *left* side of the figure shows the ratio plots *without lead-absorber* and the *right* side of the figure shows the ratio plots *with lead-absorber*.

As shown in the left side of the figure 4.3, the mean of R and R^* is about one (R is equal to R^*) for the energy from 50 MeV to 200 MeV means that when the electrons pass through the detector they lost almost same amount of energy in both scintillator tiles. However, in the right side of the figure 4.3, the mean of R and R^* is changing. At low energies (50, 100 MeV), when we use lead-absorber, the ratios above 2, the distribution of R^* is greater than R due to the most of the particles are stopped in the lead-absorber. The lead-absorber shows the electrons, with energies greater than 150 MeV, produce R (blue) distribution with *high tail* and *slope*. The dominant energy loss process is multiple scattering in scintillators at these energies.

4.3.2 Simulation of gamma without / with lead absorber for different energies

In this section, the detector geometries shown in figure 4.1 is used and the primary particles are *gamma* with different energies (50, 100, 150 and 200 MeV).



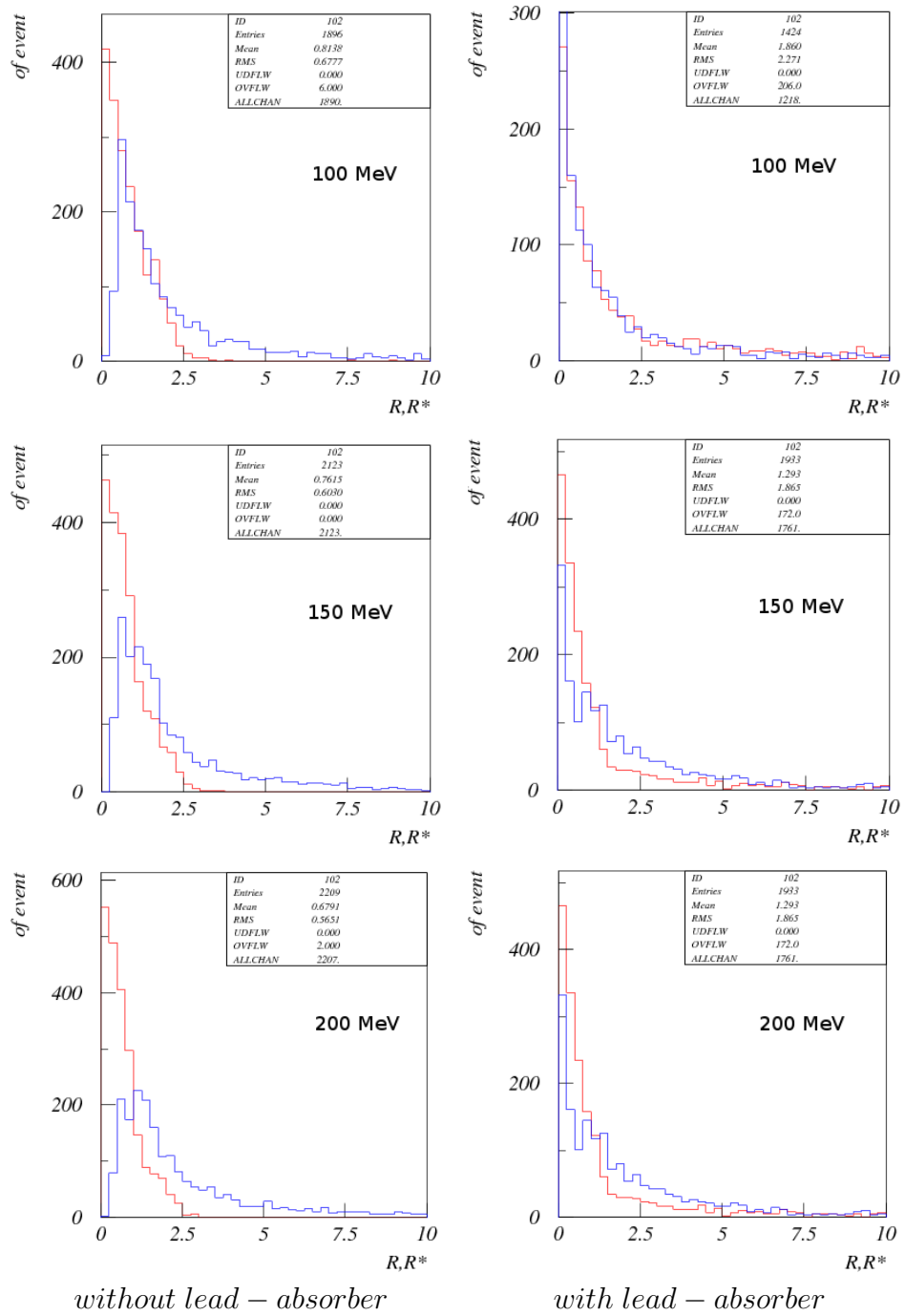


Figure 4.4: These plots, created by using 100k *gamma* with 50, 100, 150 and 200 MeV energies, represent the ratios R (blue), R* (red). The *left* side of the figure shows the ratio plots *without lead-absorber* and the *right* side of the figure shows the ratio plots *with lead-absorber*.

In the left side of the figure 4.4, the mean of R and R^* is not equal when we consider γ for the energy from 50 MeV to 200 MeV. The simulation results of R and R^* depict that R is greater than R^* for the energies of the particles is greater than 150 MeV. The dominant energy loss process is inverse Compton at these energies. However, when we use lead-absorber in front of the bottom scintillator, the ratio plots (R , R^*) have *same slope* and *tail* at low energies ($< 100\text{MeV}$), and the curvature is almost symmetric. The interaction probability of gamma particle is less than electron's at same energy(100MeV). Most probable processes are pair production and Compton scattering in scintillator. Secondary particles, are produced by Compton and pair production, lose their energy by ionization and multiple scattering processes.

When we use lead absorber in front of the bottom scintillator, which produces secondary particles either by Compton or pair production in lead, so that there will be more energy deposited in the second scintillator. The simulation results of the ratios, is shown in figure 4.4, R is greater than R^* for energies of particles is greater than 150 MeV .

4.3.3 Simulation results of e / γ with lead absorber

As shown in the figure 4.5, when the particle's energy is greater than 150 MeV, The ratio of R is bigger than R^* for e and γ , means that one can not separate e from γ .

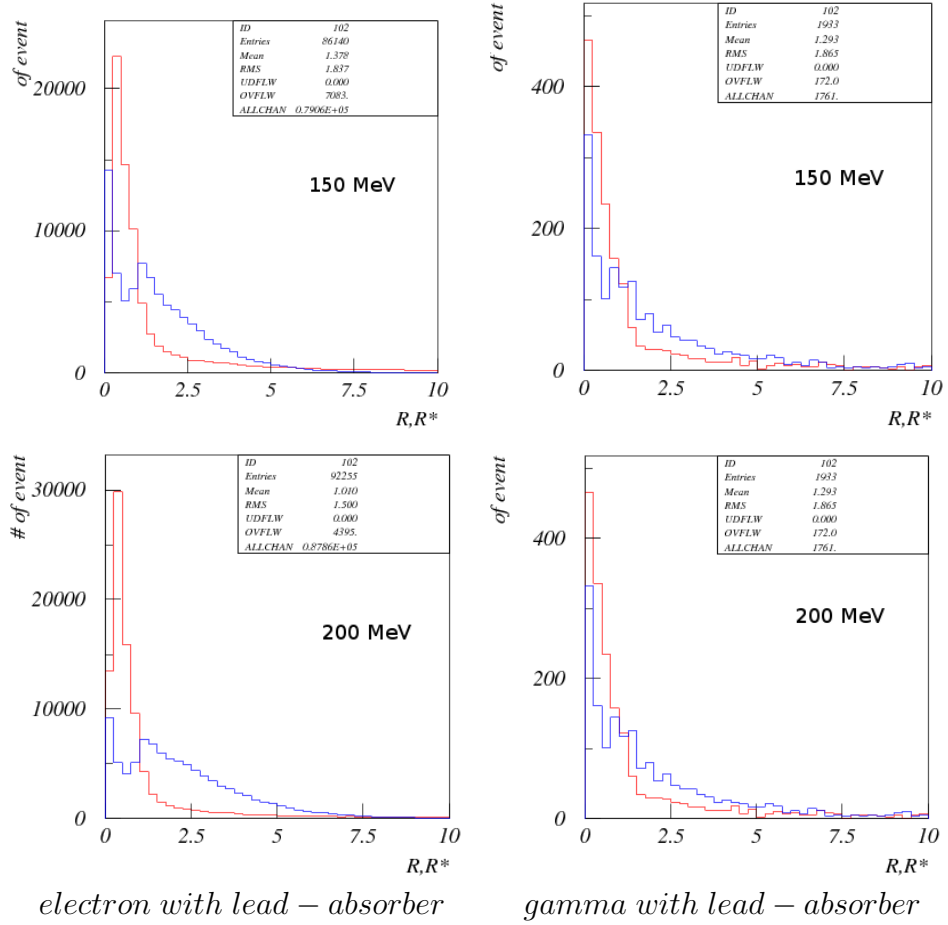


Figure 4.5: These plots, created by using 100k *electron* and *gamma* with 150 and 200 MeV energies, represent the ratios R (blue), R^* (red). The *left* side of the figure shows the ratio plots *without lead-absorber* and the *right* side of the figure shows the ratio plots *with lead-absorber*.

4.3.4 Simulation results of muon with lead absorber at 200 MeV

One can separate electron-gamma from muon by using lead absorber in front of second scintillator. Muons are weakly interacting particles so they have one peak in both scintillator tiles. For this reason the ratios R and R^* are about one is shown in figure 4.6. Electrons or gammas produce new particles leading one of the processes (Bremsstrahlung ,Compton or Pair production,...), which causes multi-peak in second scintillator. By using multi-peak signal method, one can separate muon from electron-gamma.

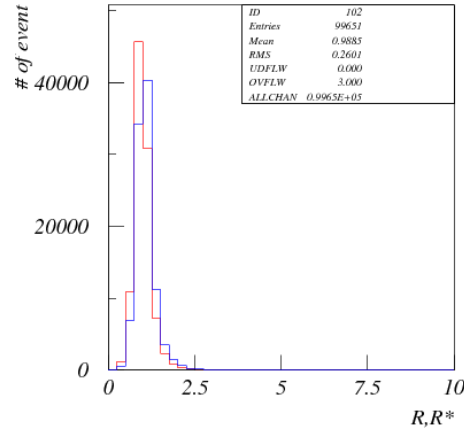


Figure 4.6: These plots, created by using 100k *muon* with 200 MeV energies, represent the ratios R (blue), R^* (red).

CHAPTER 5

THE DATA ACQUISITION

This section is an overview of the data acquisition (DAQ) system. There is two option to start the DAQ. The first option is described in the next paragraph.

A particle passing through an organic scintillator will cause a tiny flash of light. This flash of light is guided to enter a Photomultiplier tube (e.g., Hamamatsu H5783) powered by a Cockcroft-Walton high voltage generator. An input voltage of +11.5 to +15.5 volts is converted to a high voltage in the PM tube proportional to the input voltage. This high voltage creates a tiny ($\sim 20\text{ mV}$) and transient ($\sim 10\text{ ns}$) signals. This signals are splinted two branches and one branch sent to a DAQ unit such as the trigger board. In the trigger board, this signal amplified by the amplifier (AD8014). The amplifier output then feeds the voltage comparator (“discriminator”) (LMV7219) with adjustable threshold. This discriminator produces a TTL output pulse for input signals above threshold. Because of TTL output pulse is short in time, a monostable multivibrator (HCT4538) is used to stretch the pulse ($\sim 100\text{ ns}$). This stretched TTL output pulse is used and only coincident signals from any two counters, such as $C1 - C2$, $C1 - C4$, $C3 - C4$, $C3 - C2$ are allowed to produce an output pulse. Each output pulse is usually set to last 50 ns and coincidence is defined to exist if a pulse from any one of the counter overlaps a pulse from the other one (more explanation is in the next section). If the second TTL pulse does not arrive within these fixed time interval, the coincidence does not occur and the data present in these channels can not be saved.

The signal of the other branch is also amplified and sent to 2 GSamples/s digitization and acquisition system based on low power analog sampler called Domino

Ring Sampler (DRS4) board. The analog signals are stored in a multi-capacitors as a buffer. Once a trigger occurs (external by a trigger board) the acquisition of new signals is stopped and the stored signals in the buffer are readout by an ADC [51]. A schematic view of DAQ system is shown in the figure 5.1.

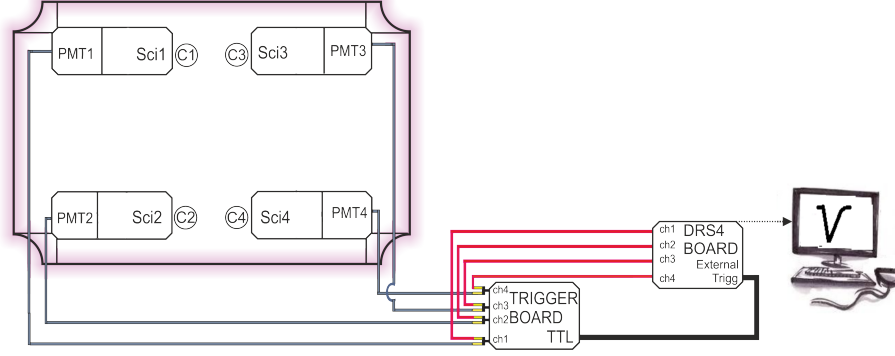


Figure 5.1: Schematic block diagram of the detector readout.

The second option, is used in this thesis, is almost same described above but this time the trigger board is removed and signals are sent directly to the DRS4 board (see fig. 5.2). Now, the DRS4 board is triggered internally means that one of the signals coming from the counters is starting the data acquisition. This option has some disadvantages such as the collection of most of spurious signals which leads to increase the file size of the data, and we need an external filter program to eliminate these spurious signals.

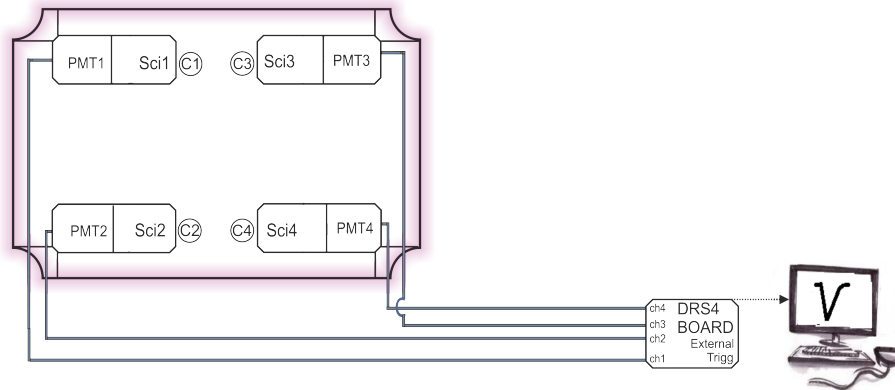


Figure 5.2: Schematic block diagram of the detector readout is used in this thesis.

5.1 Voltage Settings of Photomultiplier Tubes and Trigger Board.

The gain of PMTs is adjusted via the supplied high voltage, which is chosen with a compromise between two opposite goals: good resolution of the single particle spectrum and the widest dynamic range. In order to have a good homogeneous detector the 4 PMTs are set to same gain. Table 5.1 shows the optimization parameters of the 4 PMTs.

PMTs	Base Voltage (V)	Output Voltage (V)	Gain
PM1	13.36	900	$\sim 10^6$
PM2		782	$\sim 10^6$
PM3		805	$\sim 10^6$
PM4		805	$\sim 10^6$

Table 5.1: Optimization of PMTs voltages and gains

The PMT signals are discriminated at low level threshold providing by the trigger board for the readout. Table 5.2 shows the optimization of the 4 input channels of the trigger board.

Trigger Board Channels	Low Level Threshold Voltages (mV)
Ch1	30
Ch2	30
Ch3	30
Ch4	20

Table 5.2: Optimized parameters of the trigger board channels

5.2 Coincidence Method

The coincidence unit determines if two or more logic signals are coincident in time and generates a logic signal if true and no signal if false. The electronic determination of a coincidence between two pulses may be made in a way that

shown in the figure 5.3. Obviously, the output pulse will only be great enough to trigger the discriminator when the input pulses are sufficiently close in time to overlap. This time period determines the resolving time of the coincidence and depends on the widths of the signals and the minimum overlap required by the electronics.

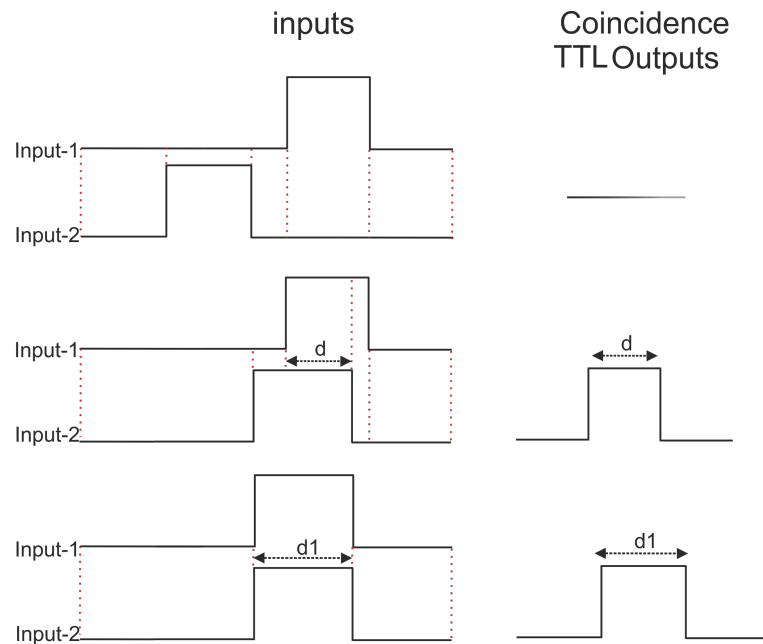


Figure 5.3: Schematic representation of coincidence signals generated by the logical AND.

Figure 5.4 illustrates a simple coincidence measuring system. The basic technique is to convert the analog signal from the detectors into a logic signal and then send these pulses to a coincidence unit.

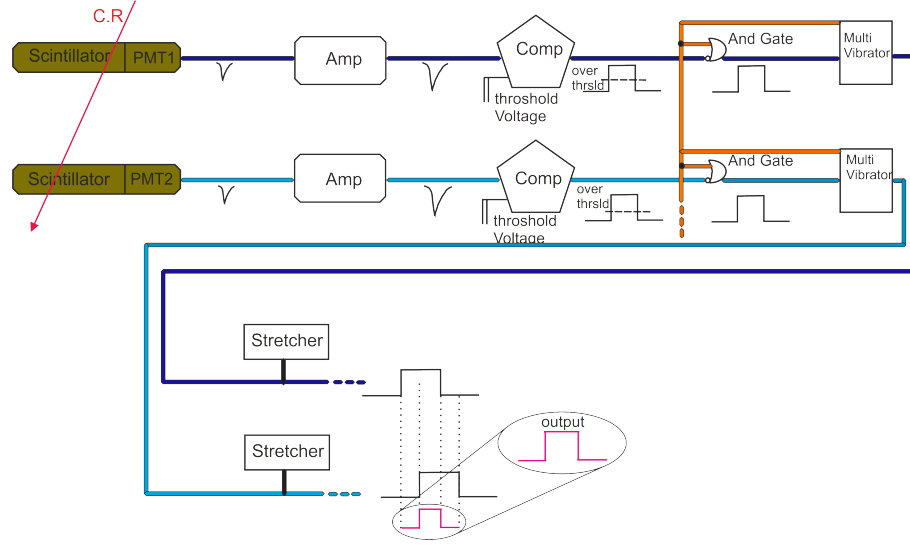


Figure 5.4: A simple electronics system for coincidence measurement.

5.3 TOF Method

Time Of Flight (TOF) is a method that measure the time that it takes for a particle to travel a distance of a medium. While a particle interact one of the scintillator counter as shown in 5.5 that starts the time counter and it will be stopped when the particle interact with the second scintillator counter. The counter telescope (shown in figure 5.5) is useful in experiments where a comparatively small number of wanted particles is to be counted in a large background of unwanted radiations. The resolving time of the coincidence circuits, which follows the counters, is useful to eliminate the spurious counts recorded due to the random coincidence of counts in the individual detectors.

The time of flight technique is also useful to discriminate the particle direction (*up-going or down-going*). If the particle hit the C1 firstly, then C2 means the particle is going to *up-ward* direction, the expected result of the time difference ($C1-C2$) should *negative*, if not, the particle is going to *down-ward* direction.

Figure 5.6 shows the method used in this thesis, which uses the line information to calculate the time of flight. The signals are registered by using DRS4 board and then plotted by *qtplot* program to see the time difference between

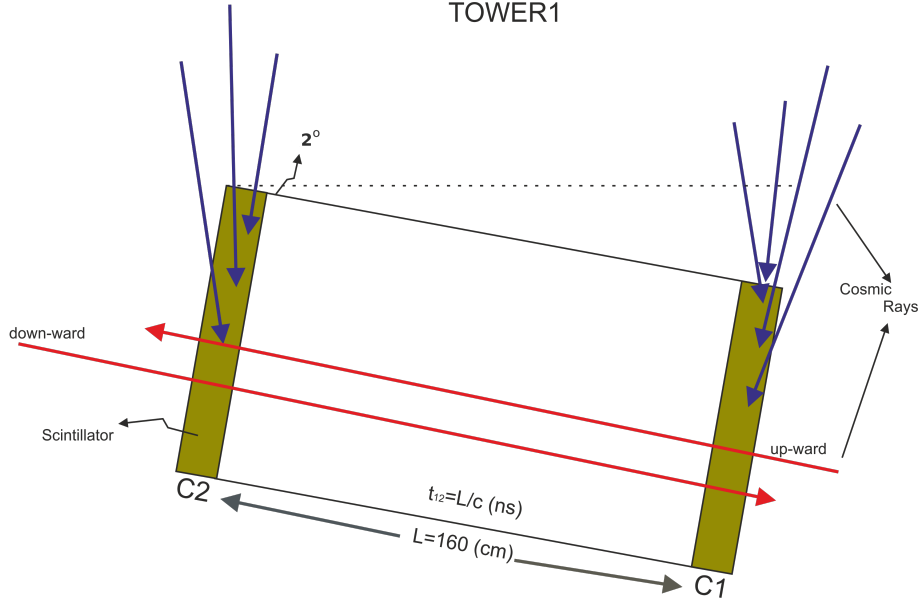


Figure 5.5: Schematic view of a tower.

two counters. If the signals are greater than the threshold voltage, the analysis program stores the first two points (voltage axes labeled as $dmax$ and $dmaxs$, and time axes labeled as $tmax$ and $tmaxs$) just below the threshold value, and draw a line which crosses the time axis. This point registered as t_0 . The difference of t_0 gives us the time of flight between two counters.

The other method, called tof, used in this thesis is almost same described above (called toff) but in this method the program firstly finds the absolute minimum of the signal then store the first 6 points starting backward direction from the absolute minimum. Then it finds the t_0 by using the *least-square* fit algorithm [52]. Figure 5.7 shows the scheme of this algorithm which computed the tof is about 5.2 ns for a *down-going* particle.

5.4 Flux Calculation

Derivation of count rate to flux formula:

To derive a formula to convert from count rate to flux, imagine a really small area A , on the bottom panel of the two that make up the vertical pair of scintil-

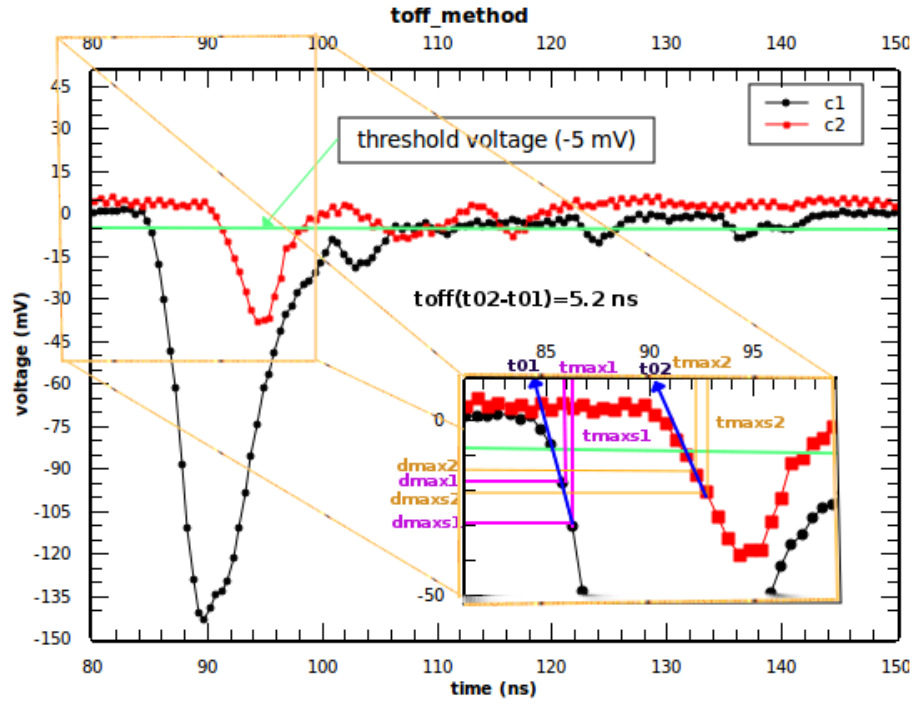


Figure 5.6: Time of flight, (toff), calculation method used in this thesis. Tile separation is 160 cm.

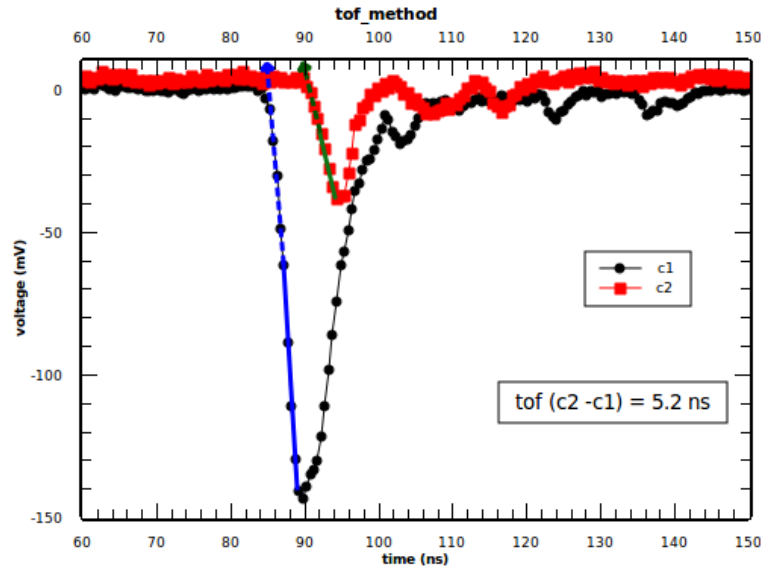


Figure 5.7: Time of flight (tof) calculation method used in this thesis. Tile separation is 160 cm. The arrows indicate the method works backward direction from the absolute minimum.

lator panels. Now, imagine a sphere (indicated in black in the picture) that has its center at that point with a radius equal to the distance d between the panels (as shown in figure 5.8).

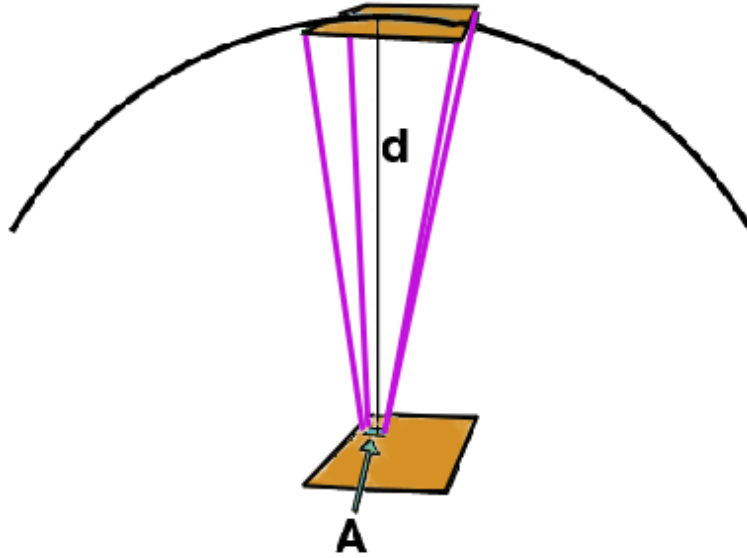


Figure 5.8: Calculation of flux by using two scintillator tiles.

In principle, the cosmic ray particles from all directions can intersect A. Obviously to get to A, these particles must also go through the wall of the imaginary sphere. But of all the particles that go through A, the fraction of particles that go through A that also go through the top panel is approximately given by the area of the top panel divided by the area of the sphere.

$$f = \frac{(\text{area of top panel})}{4\pi d^2} \quad (5.1)$$

The total count rate in our counter is now the total rate R_A of particles that go through A, times the fraction f, times the number of ways one can choose a different small area A. The number of ways one can choose a different small area A is the area of the bottom panel divided by the area of A, so the total count rate is:

$$\begin{aligned} \text{count rate} &= \frac{R_A f (\text{area of bottom panel})}{A} \\ &= \frac{R_A (\text{area of top panel}) (\text{area of bottom panel})}{4\pi d^2 A} \end{aligned} \quad (5.2)$$

where we substituted what f was. The rate of particles going through one unit of area R_{unit} is:

$$R_{unit} = \frac{R_A}{A}$$

The flux $\Phi_{C.R}$ is defined as the rate of cosmic ray particles per unit area per unit of solid angle (a steradian). A full sphere has 4π steradians, so we get:

$$\Phi_{C.R} = \frac{R_{unit}}{4\pi}$$

which gives :

$$count\ rate = \Phi_{C.R} \frac{(area\ of\ top\ panel)(area\ of\ bottom\ panel)}{d^2} \quad (5.3)$$

The *count rate* is what we measure. As you can see, it has the flux $\Phi_{C.R}$ and some numbers (the areas of the panels and the distance between them) that depend on our specific apparatus. If we want to calculate the flux, then we need to invert the formula above [53]. We obtain:

$$\Phi_{C.R} = \frac{(count\ rate)d^2}{(area\ of\ top\ panel)(area\ of\ bottom\ panel)} \quad (5.4)$$

Now let's re-write the flux formula in the following way;

$$\Phi = \frac{N_{C.R}}{S\Delta\Omega\Delta t} \quad (5.5)$$

where $N_{C.R}$ is the number of cosmic rays, S is the area of a tile, the solid angle, $\Delta\Omega$, is defined as

$$\Delta\Omega = \frac{S}{d^2} \quad (5.6)$$

and Δt is the total live time. Now we can calculate the cosmic ray flux for *down-ward* particles coming at 88° and the total live time $\Delta t = 914$ hours $= 3290400$ seconds. The area $S = 19 \times 19 \text{ cm}^2 = 361 \text{ cm}^2$ and tiles separation $d = 160 \text{ cm}$ then

$$\begin{aligned}\Phi_{(88^\circ)} &= \frac{d^2 N_{C.R}}{S^2 \Delta t} \\ &= \frac{25600 \text{ cm}^2 \times 54}{130321 \text{ cm}^4 \times 3290400 \text{ s}} \\ &= 3 \cdot 22 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\end{aligned}\tag{5.7}$$

the experimental error comes only from the number of counted events since the other numbers are constant. So the error can be calculated by

$$\begin{aligned}\text{Error} &= \frac{d^2 / (S^2 \Delta t)}{\sqrt{N_{C.R}}} \\ &= \frac{25600 \text{ cm}^2 / (130321 \text{ cm}^4 \times 3290400 \text{ s})}{\sqrt{54}} \\ &= 5 \cdot 97 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\end{aligned}\tag{5.8}$$

The total flux can be written as

$$\Phi_{(88^\circ)} = 3 \cdot 22 \times 10^{-6} \pm 5 \cdot 97 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\tag{5.9}$$

5.5 DAQ Program

A simple data acquisition program of the DRS4 Board, is based on C++ programming language, is written by Stefan Ritt. This program is not enough to register all signals coming simultaneously from 4 channels, then we improved this program to our experiment so that digitize the all analog signals (see figure 5.9)

and record the timing information of each event as shown in table 5.4.

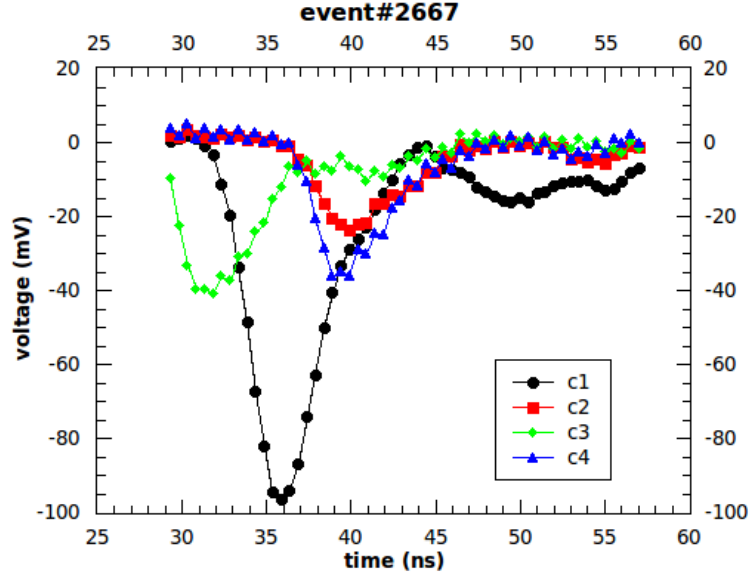


Figure 5.9: Reconstructed signal by using DRS4 daq program.

Firstly the program scans all usb ports to find a DRS4 board connection, if it finds a board is connected then initialize the board and it takes all input parameters such as a *file name* to store all waves, *sampling frequency* (from 1 GSamples/s to 5GSamples/s), *trigger mode* {internal (anyone of the channels) or external (trigger board)}, *trigger level* of the signal, *trigger delay* between signals and *event number* interactively from command screen or you can also create an input card to starts the DAQ program. The input parameters used for this thesis data is shown in table 5.3.

Parameter	Value	Unit
Sampling Frequency	2	GHz
External Trigger	0	
Internal Trigger	1	
Trigger Channel (<i>only if internal = 1</i>)	0 (means channel 1 is selected)	
Internal Trigger Level	-5	mV
Trigger Delay	100 (means the cursor is on the middle of the scope screen)	ns
Number of Events	10000000	

Table 5.3: Input parameters of the DAQ program.

Table 5.4 shows the output data format of the data acquisition program.

Event#				
Year				
Mount				
Day				
Hour				
Minute				
Second				
# of points in the signal				
time (ns)	ch1 (mV)	ch2 (mV)	ch3 (mV)	ch4 (mV)

Table 5.4: Output data format of the DAQ program.

5.6 Filter Program

There is lots of spurious signals in the raw data caused by leakage of light, electronic noises coming from the DAQ components (the resolution of these type signals is around 2 ns) and some spikes from DRS4 Board. After sampling a pulse, some residual charge remains in the capacitors on the next turn and can mimic wrong pulses in the DRS chip. This ghost pulse rate is 2% at 2 GHz. We need an external filter program to eliminate these type spikes from the data. If not, this spikes cause to wrong calculation of time of flight in the analysis. Figure 5.10 shows the spike coming with the signal at channel 1.

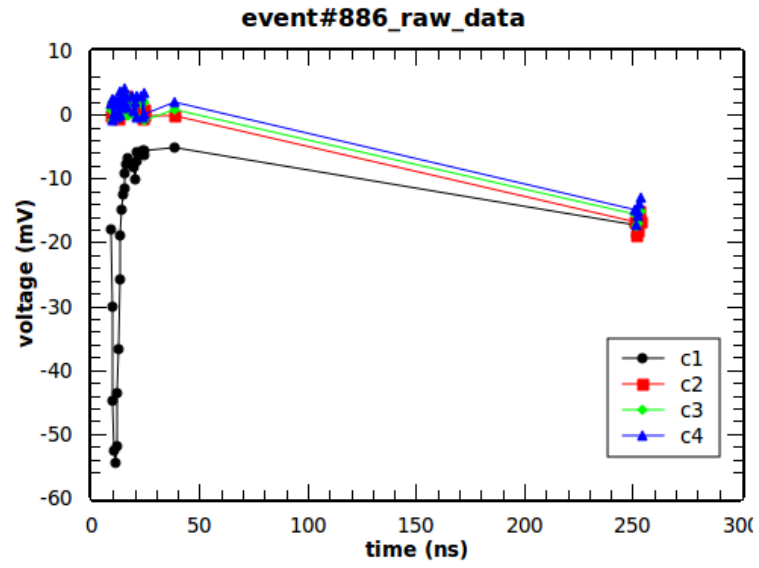


Figure 5.10: Spike caused by DRS4 in the channel 1.

After applying the filter program to the data, the spike, was around 251 ns, are removed from the signal is shown in figure 5.11.

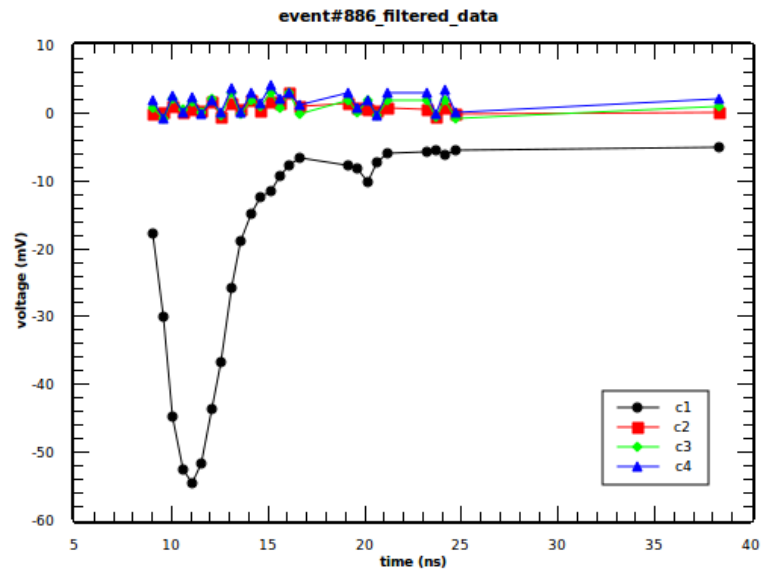


Figure 5.11: Spike removed by the filter program.

CHAPTER 6

RESULT AND DISCUSS

In this chapter the time of flight informations have been used to determine particle directions (*up-ward* or *down-ward*). The expected time resolution of two tiles is around 5 ns due to the distance between two tiles $L = 160$ cm; shown in figure 5.5, the difference of the signal arrival time at each of four tiles, Δt_{12} , Δt_{13} , Δt_{34} and Δt_{32} were recorded. Figure 6.1 shows the deposited charges on each tiles. The charge information is used for the particle selection. The peak is caused by the particles which have less energy and they crossed just in front of the PMT window so they can not reach the other tile, and the tail is due to the more energetic particles hits only one tile at the edge of the scintillator tile and some spikes cause this type charge release. For these reasons we applied the charge cuts for each tiles and resultant total charges deposited on each tiles are shown in the figure 6.2.

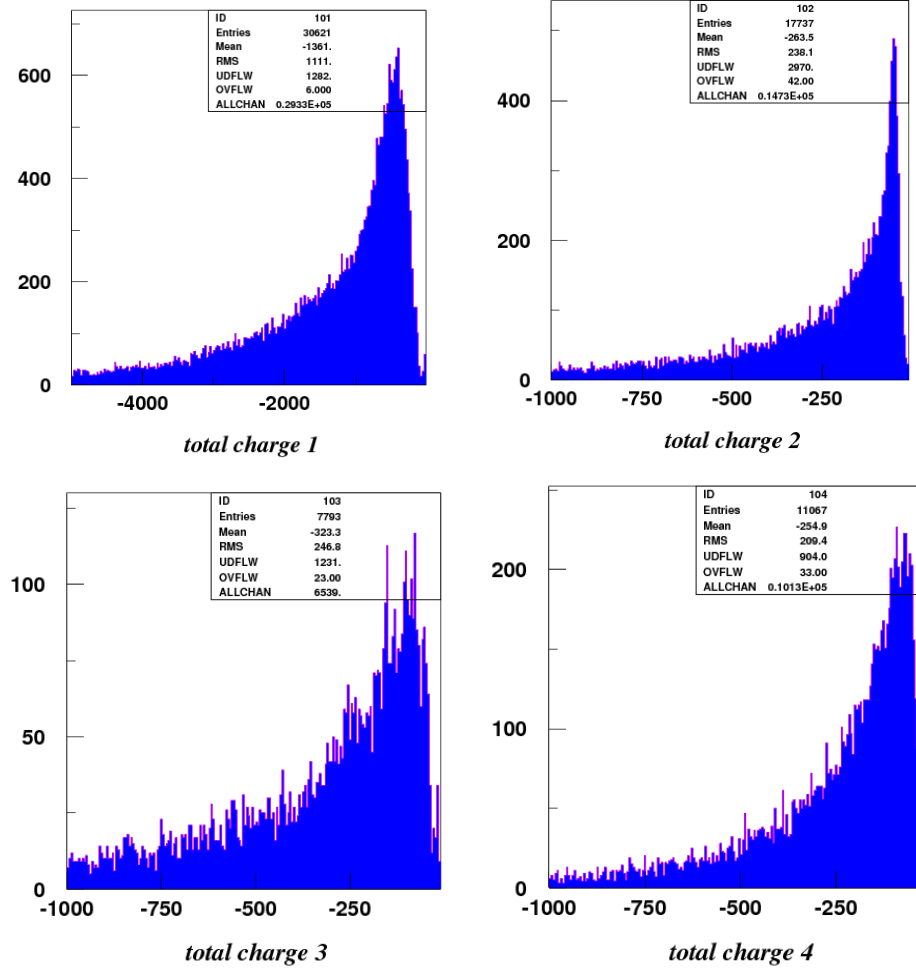


Figure 6.1: Charge deposited on each tiles. The y-axis represents the number of entries and x-axis represents the charge deposited in tile (in mV).

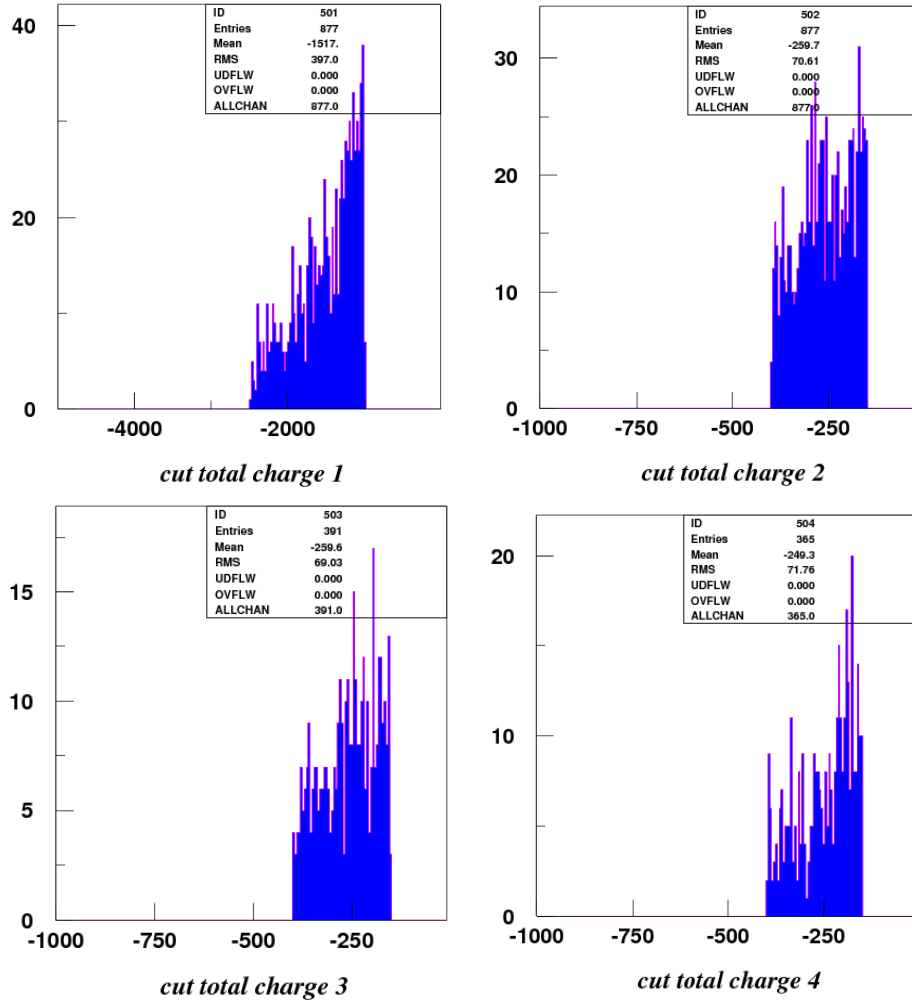


Figure 6.2: Charge deposited on each tiles after applying the charge cut. The y-axis represents the number of entries and x-axis represents the charge deposited in tile (in mV).

Because of having good time resolution, each tower is capable of discriminating the direction of tracks which are going up or down by measuring the time of flight between any two tiles.

Figure 6.3 and 6.4 represent the results of time of flight methods, are $toff$ and tof , are produced when we apply only the charge cut selection criteria. The peak around $+5 ns$ and $-5 ns$ are correspond to the *down-going* and *up-going* particles, respectively. The other peaks are our background that is caused by vertical tracks is around $0 ns$, the parallel tracks is accumulates around $\pm 3 ns$ and the tracks where the particles hit the corner of one tile. The scheme of the tracks is shown

in the figure 5.5.

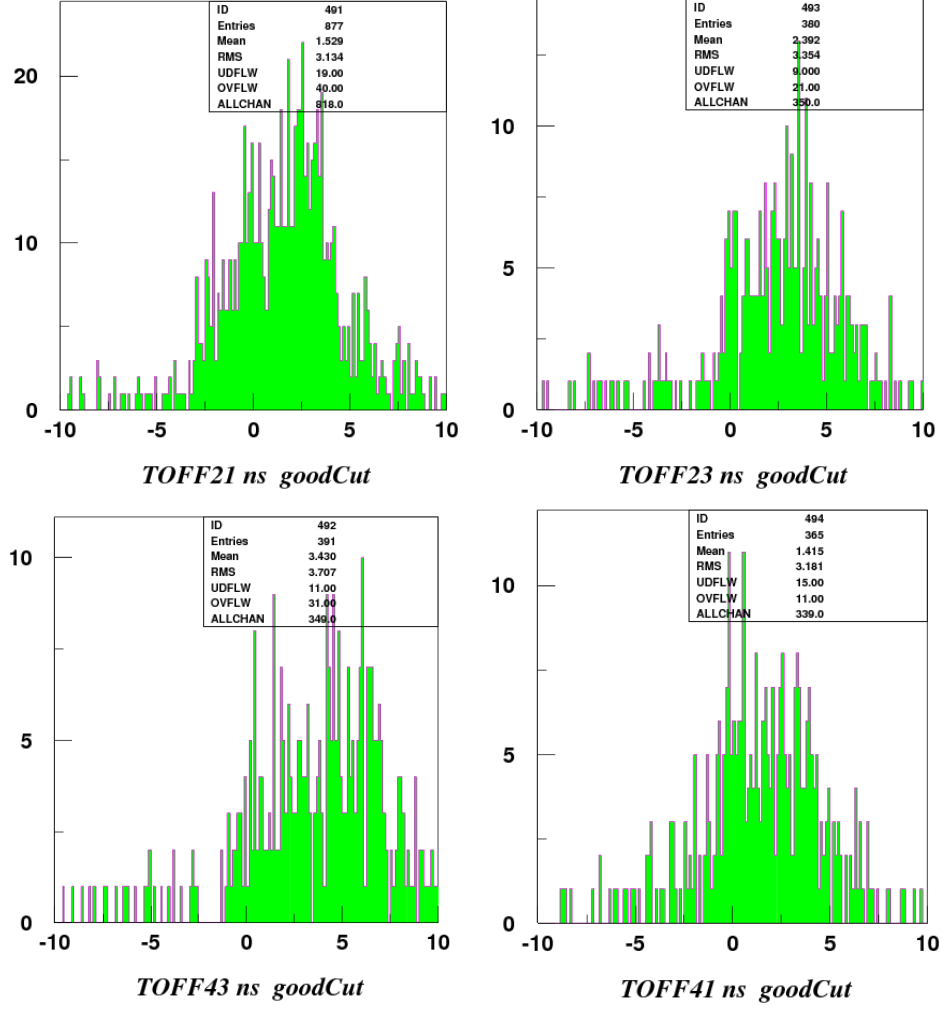


Figure 6.3: Time of flight differences between the tiles Δt_{12} , Δt_{14} , Δt_{34} and Δt_{32} in the towers pointing a zenith angle 92° . The two peaks around $+5$ ns and -5 ns correspond to up-going and down-going particle tracks, respectively. The other peaks are caused by parallel tracks, vertical tracks and when the particle hits to the corner of the tiles (see fig. 5.5). These plots are produced by using **toff method** described in section 5.2.

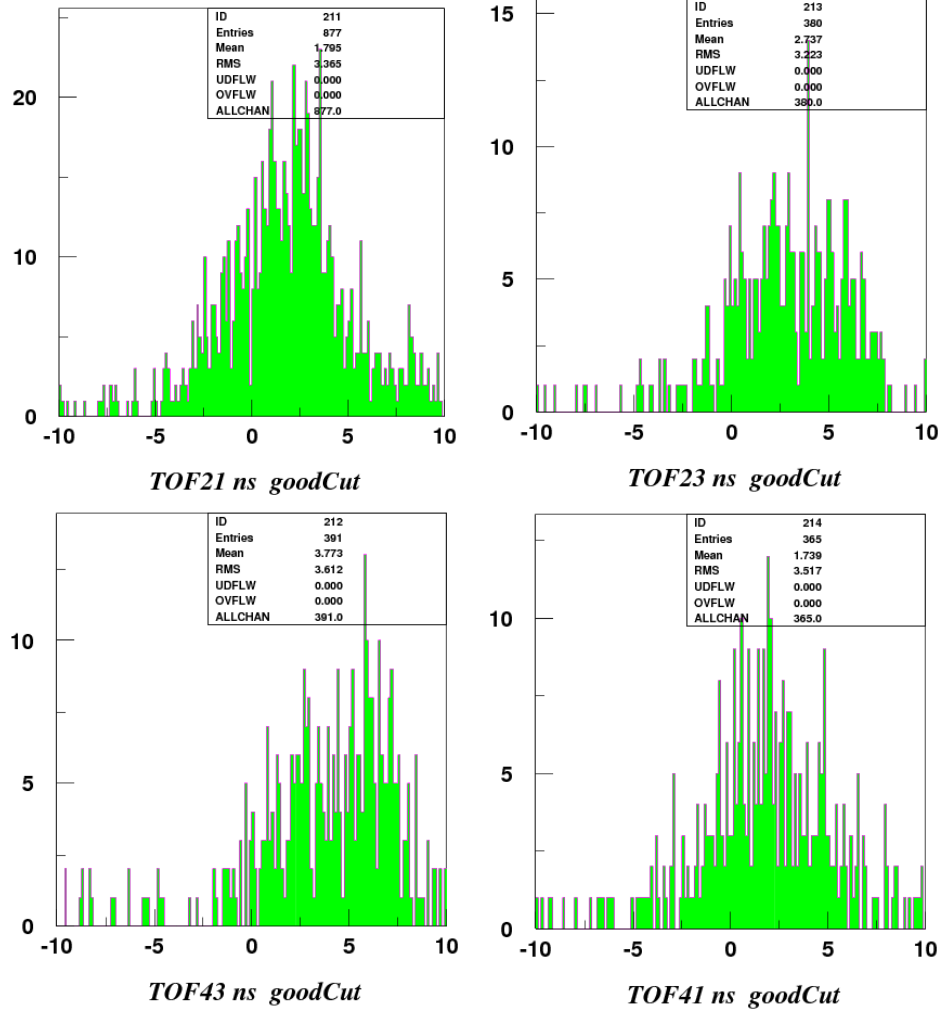


Figure 6.4: Time of flight differences between the tiles Δt_{12} , Δt_{14} , Δt_{34} and Δt_{32} in the towers pointing a zenith angle 92° . The two peaks around $+5$ ns and -5 ns correspond to up-going and down-going particle tracks, respectively. The other peaks are caused by parallel tracks, vertical tracks and when the particle hits to the corner of the tiles (see fig. 5.5). These plots are produced by using **tof method** described in section 5.2.

Figure 6.5 and 6.6 shows the time of flight results which are produced by applying the time of flight cut together with charge cut on the signals. They are indicating only the *down-going* particles at 88° incident angle.

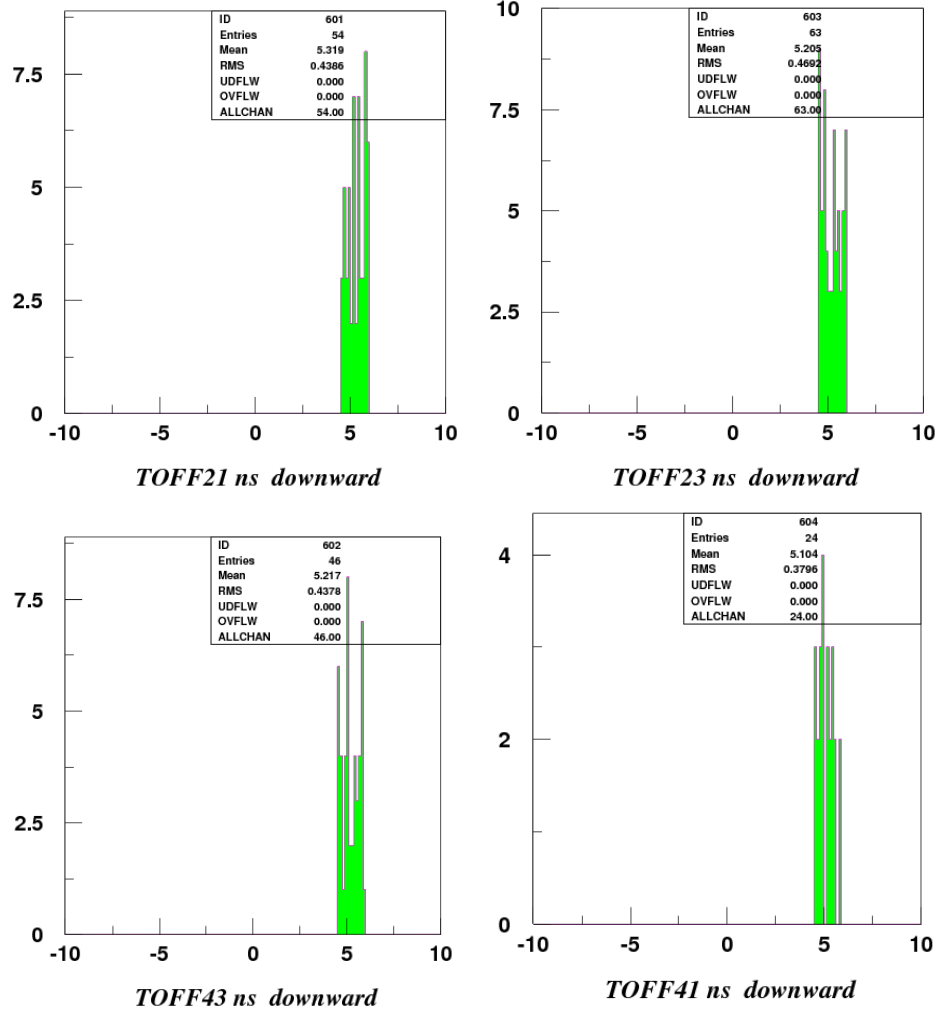


Figure 6.5: Time of flight differences between the tiles Δt_{12} , Δt_{14} , Δt_{34} and Δt_{32} in the towers pointing a zenith angle 92° . The peak at +5 ns correspond to down-going particle tracks. These plots are produced by using **toff method** described in section 5.2.

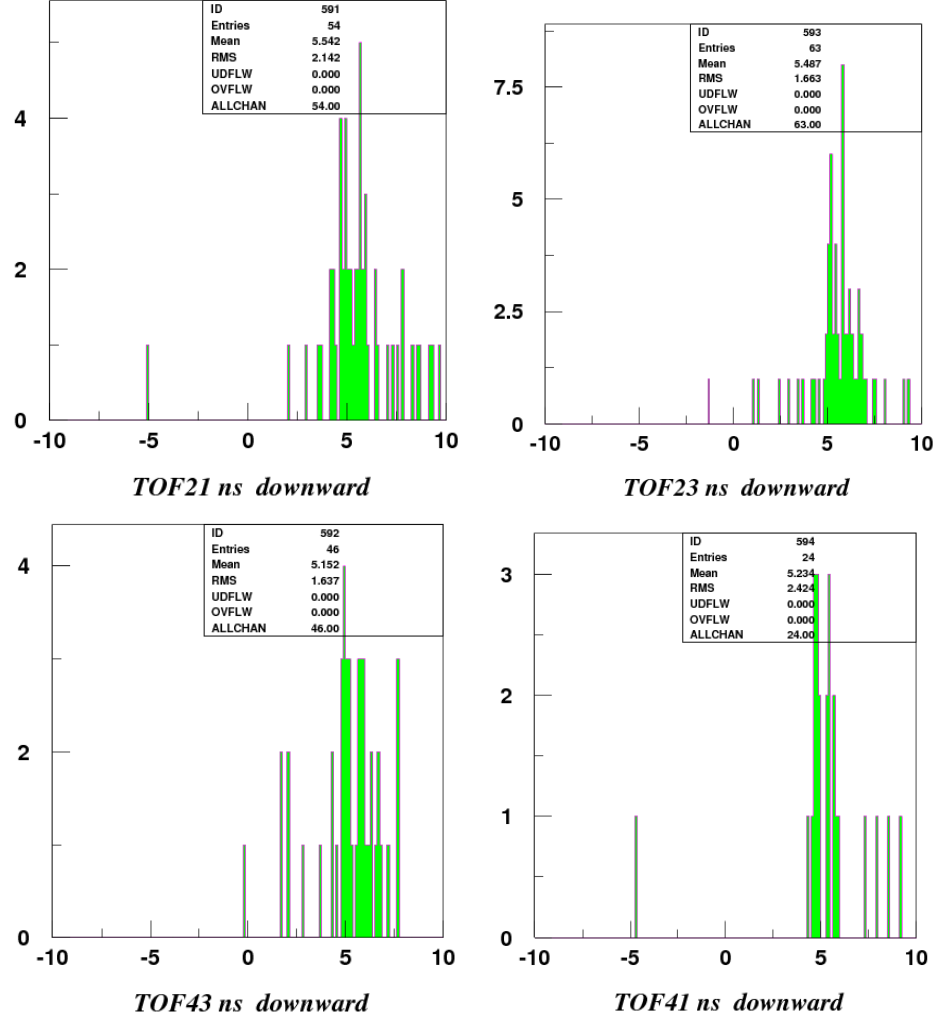


Figure 6.6: Time of flight differences between the tiles Δt_{12} , Δt_{14} , Δt_{34} and Δt_{32} in the towers pointing a zenith angle 92° . The peak at +5 ns correspond to down-going particle tracks. These plots are produced by using **tof method** described in section 5.2.

The cosmic ray flux of *down-going* particles was measured by using the towers pointing at 92° zenith angle and compared with the results from the other experiments is shown in figure 6.7. If we compare this result with [54], one can see that there is small discrepancy due to the selection cuts on DRS4 signals and tof methods (i.e. low amplitude signals are discarded because of the poor light collection, different gain which effects the trigger threshold voltage). There is also small contribution comes from the active surface of the scintillator counters. If we remove the inactive regions (i.e. corners of the scintillator, the active dimension

of the scintillator tile is $S = (18 \times 15 + 27) \text{ cm}^2 = 297 \text{ cm}^2$ and tiles separation $d = 160 \text{ cm}$ then the flux would be

$$\begin{aligned}
 \Phi_{(88^\circ)} &= \frac{d^2 N_{C.R}}{S^2 \Delta t} \\
 &= \frac{25600 \text{ cm}^2 \times 54}{88209 \text{ cm}^4 \times 3290400 \text{ s}} \\
 &= 4 \cdot 76 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
 \end{aligned} \tag{6.1}$$

and the error is

$$\begin{aligned}
 Error &= \frac{d^2 / (S^2 \Delta t)}{\sqrt{N_{C.R}}} \\
 &= \frac{25600 \text{ cm}^2 / (88209 \text{ cm}^4 \times 3290400 \text{ s})}{\sqrt{54}} \\
 &= 8 \cdot 82 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
 \end{aligned} \tag{6.2}$$

then the total flux can be written as

$$\Phi_{(88^\circ)} = 4 \cdot 76 \times 10^{-6} \pm 8 \cdot 82 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \tag{6.3}$$

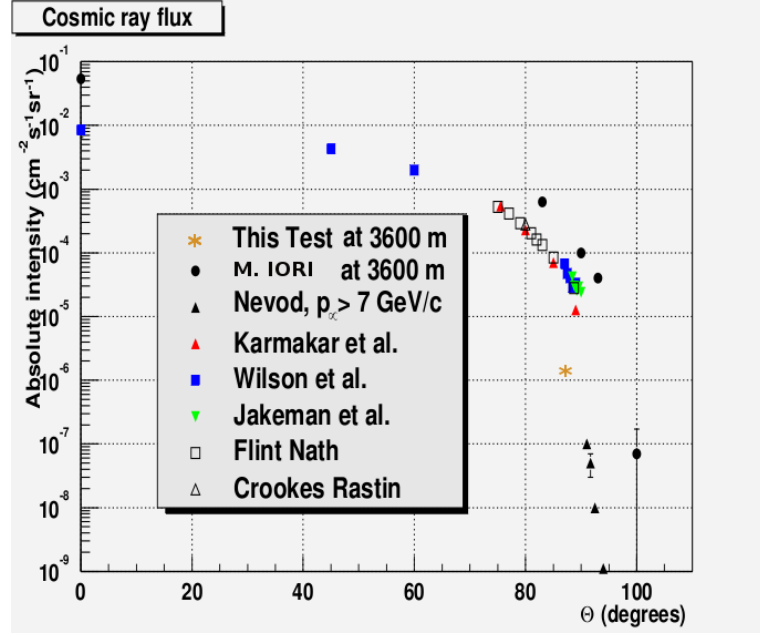


Figure 6.7: Measurement of flux at 88° incident angle in the High Altitude Jungfraujoch Station compared with results from other experiments [54].

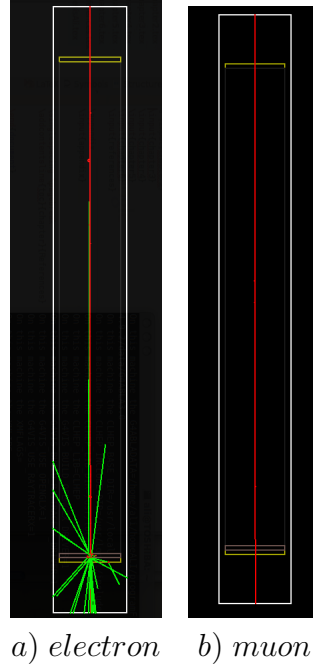


Figure 6.8: Layouts of the detectors with lead absorber and source particles are electron and muon with the 200 MeV energy.

As shown from the figure 6.8 a) when electrons pass through the lead absorber, they lose energy leading one of the processes (Compton, ionization, Bremsstrahlung,

...), is shown in the figure 6.9 a), they leads to multiple scattering and release more charges at the bottom scintillator. Unlike electrons, muons are weakly interacting particles is depicted in figure 6.8 b) and they lose their energy only the muonic processes (see fig. 6.9 b)) that leads to less charges production at the bottom scintillator.

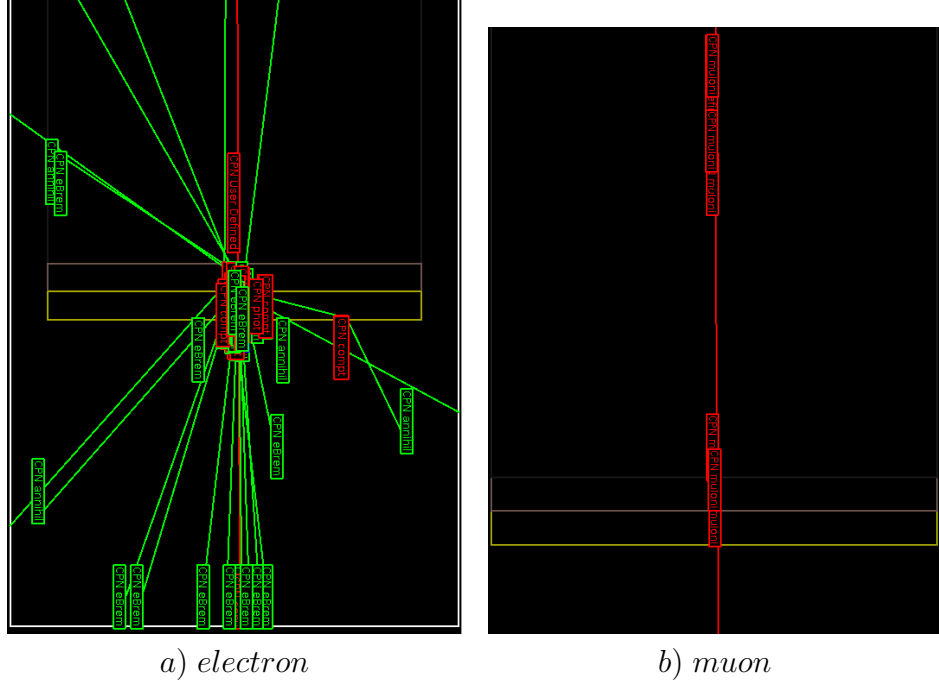


Figure 6.9: Blow-up of the bottom side of detectors with lead absorber.

The results of the particle identification capability of the prototype detector simulation study, is shown in figure 6.10, concluded that if the area under the red line (corresponds to muon densities in the shower) is extracted from the area under the blue line, the electron (γ) densities can be found.

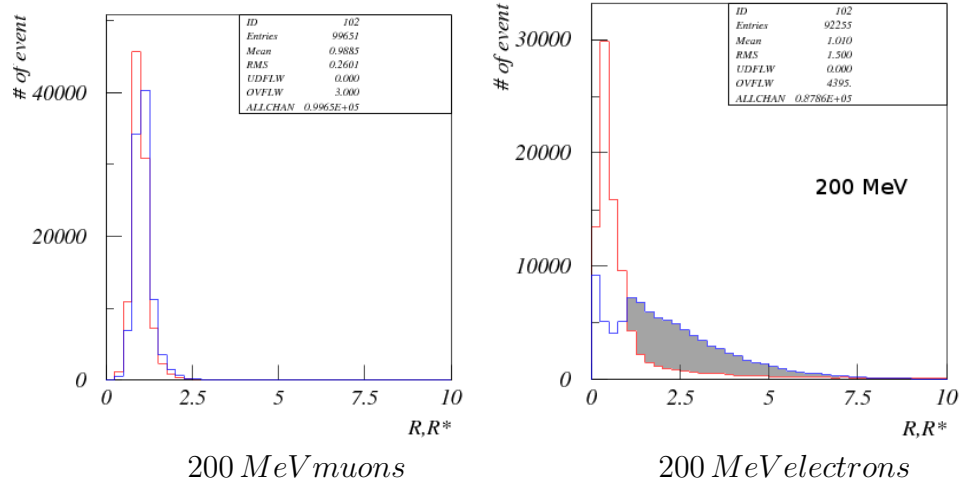


Figure 6.10: These plots, created with lead-absorber by using 100k electron and muon with 200 MeV particles, represent the ratios R (blue), R* (red). The grey filled area corresponds to the electron (& gamma) densities on the shower.

In conclusion the study shows us that the detector prototype is capable to discriminate up-going and down-going particles. The flux measurement have been done for these short live run time (3290400 seconds) without trigger board, the results show us that the prototype detector has been working stably without any problem at these hard weather conditions.

The method have been also tested to distinguish electrons from muons by using Geant4 simulation package based on Monte Carlo methods. The ratio of charge released on top and bottom scintillator tile is about one for muon and if it is greater than one which is probable electron (or gamma). The detector sensitivity is around $10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The next step is to install a lead block in front of the second scintillator at large zenith angle ($\sim 92^\circ$) to prove this simulation study, and the other step is to install the trigger board with new DRS4 board which leads to increase statistics of wanted signals and improves the the flux resolution of the detector prototype.

As a summary, thesis with based on working prototypes which have been located in 3 different locations, one in Rome, one in Bolu and one in Jungfraujoeh. The first design of the prototype and trigger board were done at the beginning in

Rome by M. Iori. Then we set up the prototype detector station at Jungfraujoch Terrace for outside tests (such as effect of the weather conditions on the electronics systems). The limitation of the DRS4 board were discovered during this test period. It did not have a protection for high voltage. But new version of DRS4 board has this protection. The trigger board and new version of DRS4 board is ready and will be connected in the next trip for the feature studies. In Bolu with BAP project, we were able to build one station so that we could do some tests locally. We have been accumulating data for more than a month with one tower with trigger board installed.

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APPENDIX A

KURARAY ORGANIC SCINTILLATOR

Kuraray's Scintillation Materials

Plastic Scintillating Fibers

SCSN Plastic Scintillators

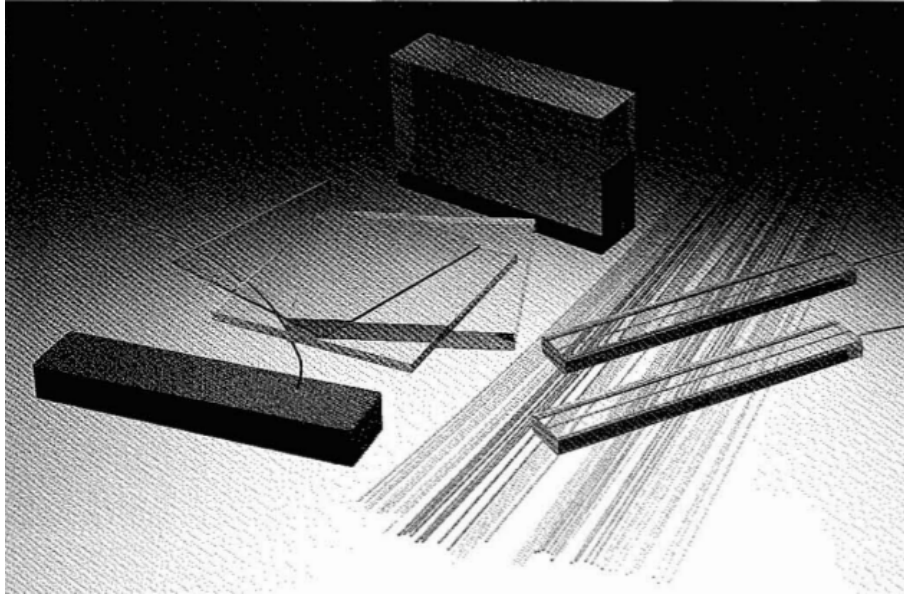
The history of Kuraray's scintillation materials dates back to 1982, when we put new plastic scintillators on the market. These unique plastic scintillators were named SCSN and gained public favor all over the world. After plastic scintillators, we developed scintillating fibers, wavelength shifting fibers and clear optical fibers in 1990. Having excellent stability of properties, Kuraray's plastic fibers are trusted by many scientists and technical experts.

As pioneer in the world, we developed multi cladding fibers which have 50% higher light yield than previous single cladding fibers in 1993. It is well-known that Multi cladding fibers contributed to improvement of properties of fiber-detectors in the field of high energy physics.

Kuraray's scintillation materials play an active part not only in the scene of high energy physics, but in the scene of atomic energy. We hope to attract attention in the fields of medicine. There is strong potential for new applications in the future.

Since we have skill in splicing WLS fibers to clear fibers and assembling fibers into bundles and blocks, we can supply fibers in suitable shapes for your detectors.

This brochure presents only basic technical data. If you have further questions, please let us know at any time. We are looking forward to supporting your works and applications.



All data presented here in is based on actual measurements performedby Kuraray Co., Ltd.

Kuraray Co., ltd. accepts no liability for damage or loss resulting from the use or misuse of this information.

Plastic Fibers

Scintillating Fibers

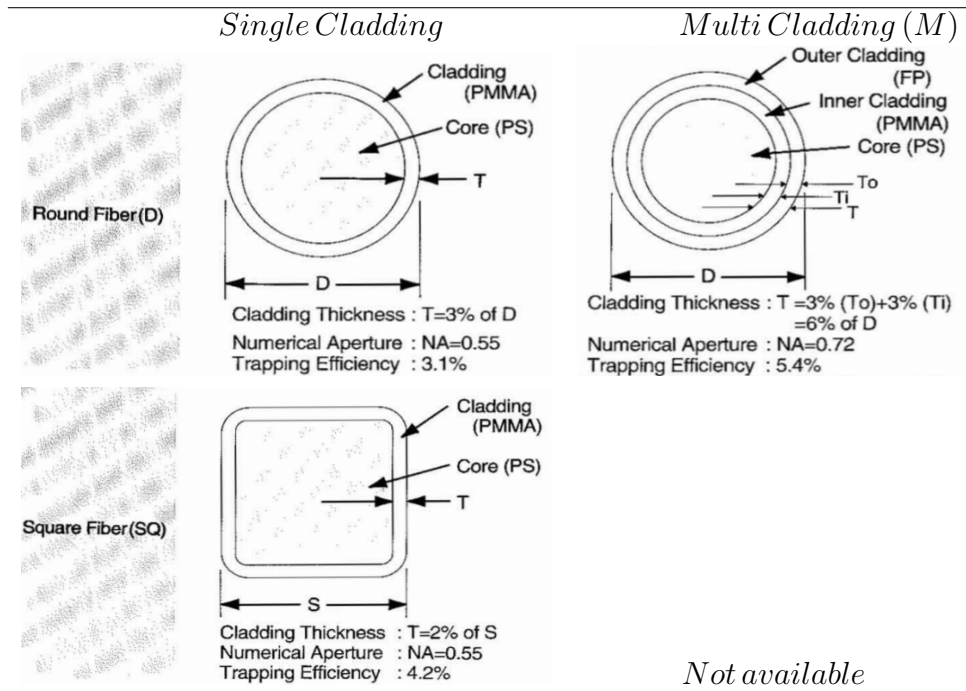
Wavelength Shifting Fibers

Clear Fiber

Materials and Structures

Materials	Material	Refractive index	Density (g/cm ³)	No. of atom per cm ³
Core	Polystyrene (PS)	$n_D = 1.59$	1.05	$C : 4.9 \times 10^{22}$ $H : 4.9 \times 10^{22}$
for single cladding	Polymethylmethacrylate (PMMA)	$n_D = 1.49$	1.19	$C : 3.6 \times 10^{22}$ $H : 5.7 \times 10^{22}$ $O : 1.4 \times 10^{22}$
inner for multi cladding				
Cladding outer for multi cladding	Fluorinated polymer (FP)	$n_D = 1.42$	1.43	

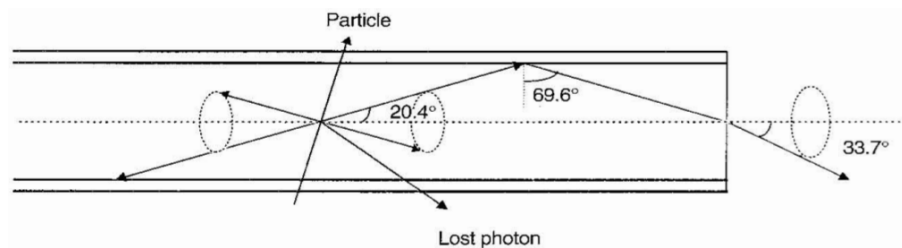
Cross-section and Cladding Thickness



Cladding and Transmission Mechanism

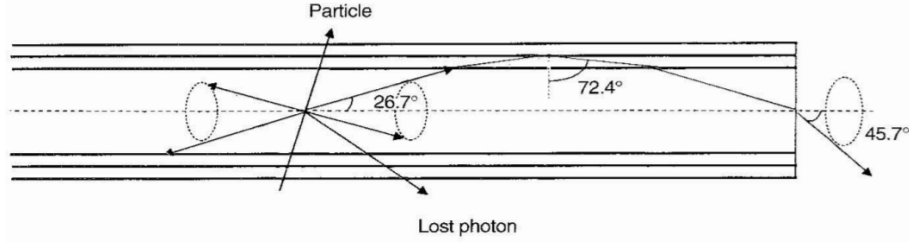
Single Cladding

Single cladding is a standard type of cladding.



Multi Cladding

Multi cladding fiber (M) has 50% higher light yield than single cladding fiber because of large trapping efficiency. Clear-PS fiber of this cladding has extremely higher NA than conventional PMMA or PS fiber, and very useful as light guide fiber. Multi cladding fiber has long attenuation length equal to single cladding fiber.



Type of Polymer Orientation of PS Core

Standard type (Non-S type)

PS core is of almost no oriented polystyrene chain and is optically isotropic and very transparent. This conventional standard type has good attenuation length, but it showed weakness against clacking caused by bending or handling during assembling.

S type (S)

Core has molecular orientation along drawing direction. This fiber is mechanically stronger against clacking at the cost of transparency. The attenuation length of this type is nearly 10% shorter than standard type.

Dimensions and Tolerance

Cross-sectional Dimension

Minimum : 0.2mm, Maximum : 2.0mm, typically as follows.

Round (Single and Multi Cladding) : 0.2, 0.5, 1.0, 1.5, 2.0mm dia.

Square (Single Cladding) : 0.2×0.2 , 0.5×0.5 , 1.0×1.0 , $2.0 \times 2.0mm$ side

Tolerance of Diameter

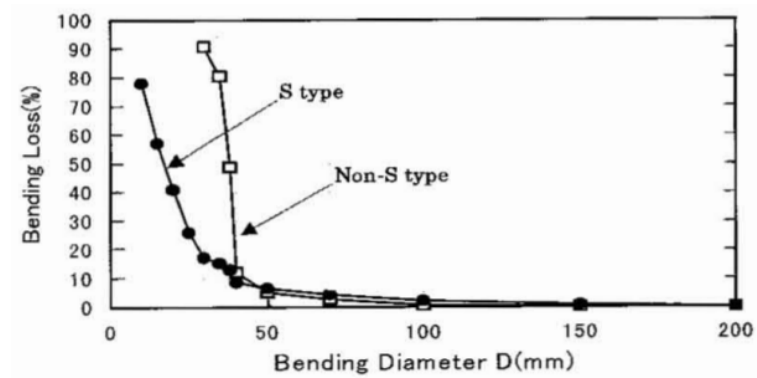
<i>Cut Fiber</i> (1 – 5m long)	$: \left \frac{\Delta D}{D} \right < 2.0\% \text{ for round fiber}$ $\left \frac{\Delta S}{S} \right < 3.0\% \text{ for square fiber}$
<i>Endless Spool Fiber</i>	$: \left \frac{3\sigma}{D} \right < 2.5\% (\sigma : rms \text{ Spool Dia.} : 300mm \text{ or } 900mm.)$

(A.1)

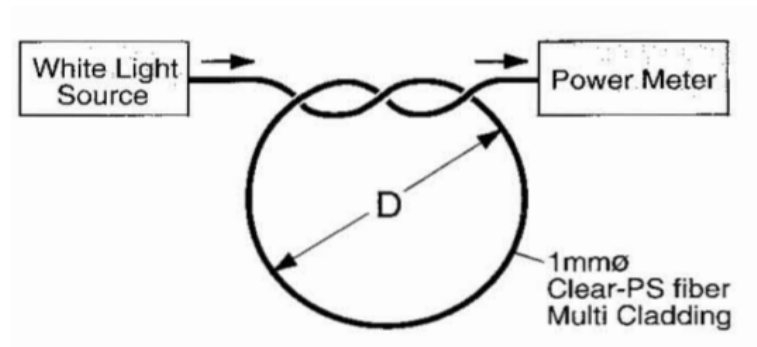
Bending Loss and Minimum Bending Diameter

Bending Loss

The following figure shows bending loss of Clear-PSM and Clear-PSMS. S type is better than Non-S type. The rapid increase of bending loss of non-S type is due to cracking of core. S type doesn't show such cracking.



Measurement Method



Minimum Bending Diameter

We recommend minimum bending diameter as the following table on safety side and long term reliability.

Type	2mmø Fiber	1mmø Fiber	0.5mmø Fiber
S type	200mm	100mm	50mm
Non-S type	400mm	200mm	100mm

Formulations

*Scintillating Fibers*¹

Description	Color	Emission Peak (nm)	Spectra	Decay Time (ns)	Att.Leng.(m) ²⁾	Characteristics
SCSF-38, SCSF-38M	blue	428	See the following figure	2.3	> 3.0	General Use
SCSF-81, SCSF-81M	blue	437		2.4	> 3.5	Long Attenuation Length
SCSF-78, SCSF-78M	blue	450		2.8	> 4.0	Long Att. Leng. and High Light Yield
SCSF-3HF(1500), SCSF-3HF(1500)M ³⁾	green	530		7	> 4.5	3HF formulation for Radiation Hardness

1) Test fibers are Non-S type, 1mm $\emptyset$.

2) Measured by using bi-alkali PMT and UV light (254 nm). Quality control is made by another measurement of the transmission loss every batch.

3) For example, "3 HF(1500)M" means the concentration of 3HF dye is 1500ppm, the cladding is Multi cladding.

*Wavelength Shifting Fibers (WLS Fibers)*⁴

Description	Color	Emission Peak (nm)	Spectra	Att.Leng.(m) ⁵⁾	Characteristics
Y-7 (100), Y-7 (100)M	green	490	See the following figure	> 3.0	Green Shifter
Y-8 (100), Y-8 (100)M	green	511		> 2.8	Green Shifter
Y-11 (200), Y-11 (200)M	green	476		> 3.5	Green Shifter (K-27 formulation)
0-2 (100), 0-2(100)M	orange	538		> 1.5	Green to Orange Shifter

4) Test fibers are Non-S type, 1mm $\emptyset$.

5) Measured by using bi-alkali PMT and blue LED (445nm).

Otherwise than descriptions mentioned above, various WLS fibers are available.

Ex. R-3 (green to red shifter, peak is 607nm), Y-9 (blue to green shifter, 485nm), B-1 (428nm), B-2 (437nm).

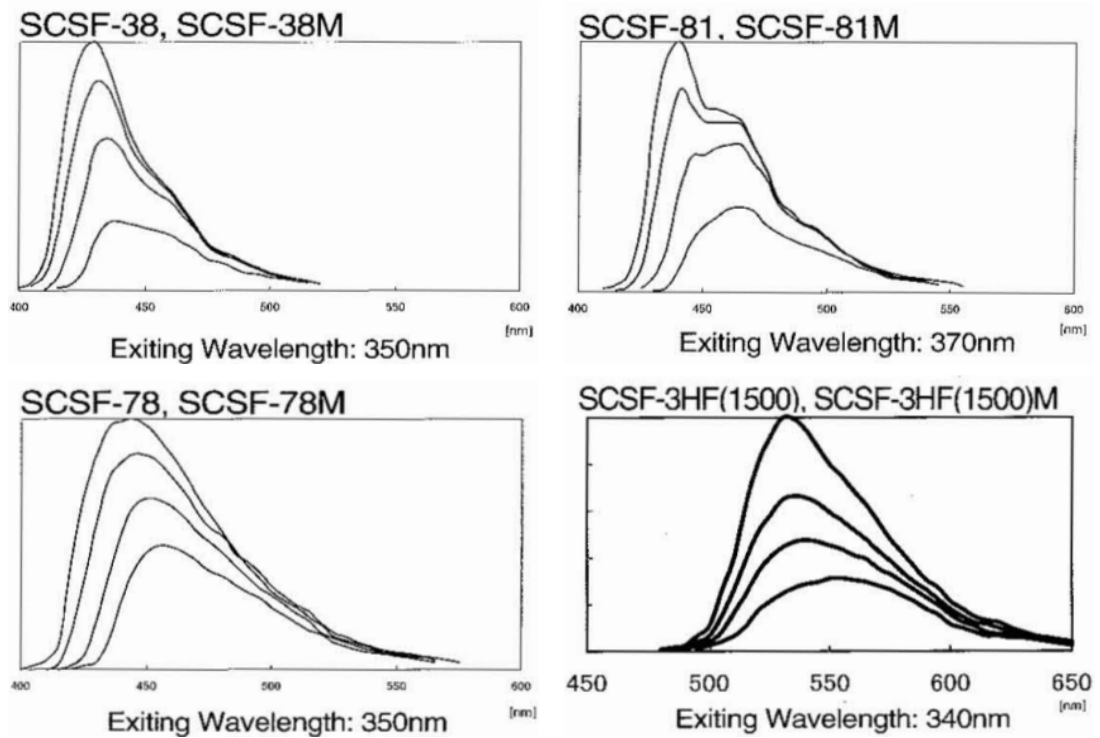
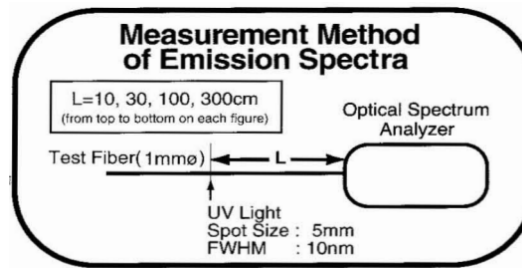
*Clear Fiber (Non-doped, Optical Fiber)*⁶

Description	Color	Emission Peak (nm)	Spectra	Att.Leng.(m)	Characteristics
Clear-PS, Clear-PSM	-	-	-	> 10.0	depend on wavelength

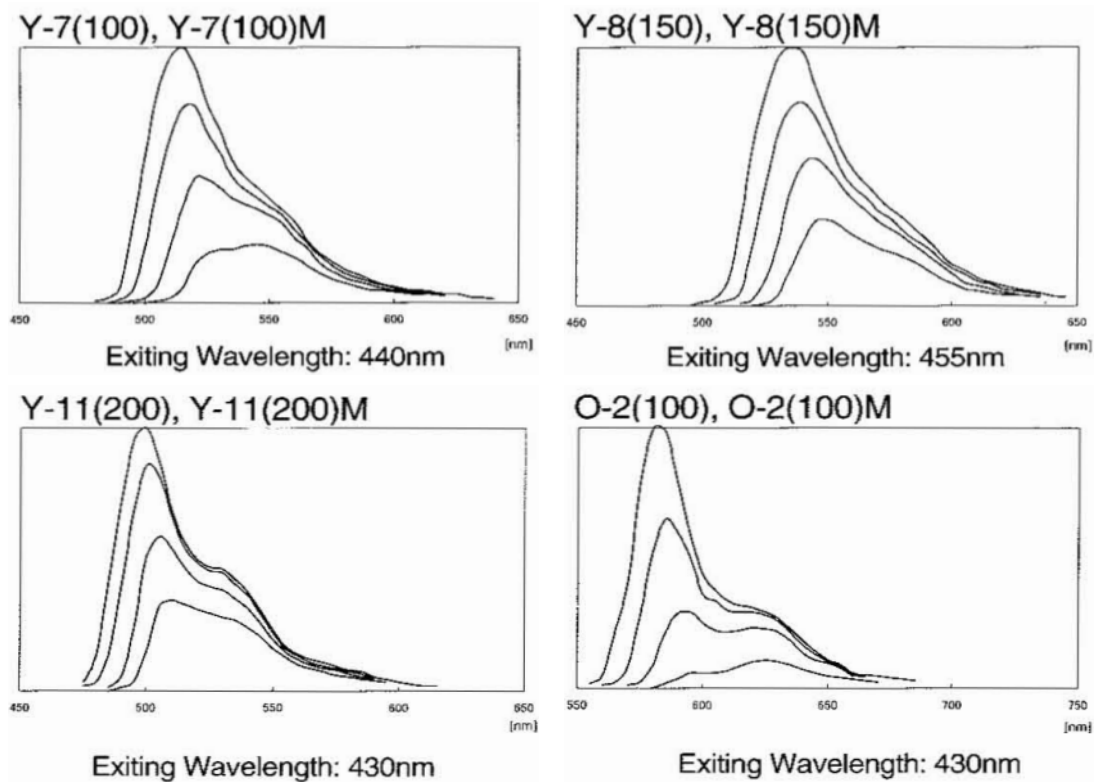
6) Test fibers are Non-S type, 1mm $\emptyset$

Transmission Loss data is shown on page 7 and 8.

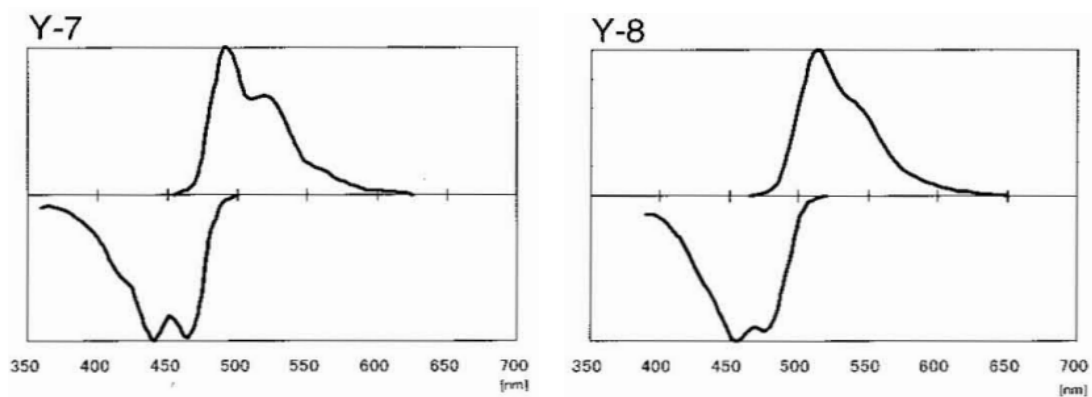
Emission Spectra

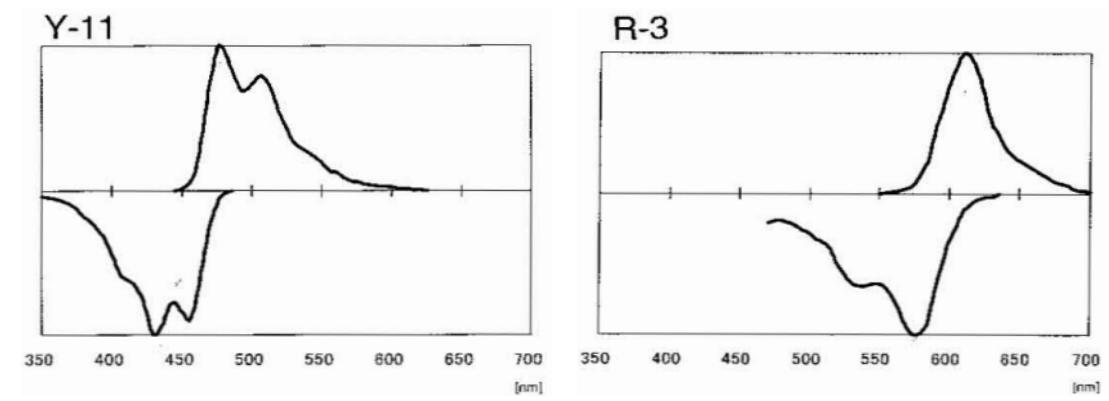


WLS Fibers



Absorption and Emission Spectra of WLS

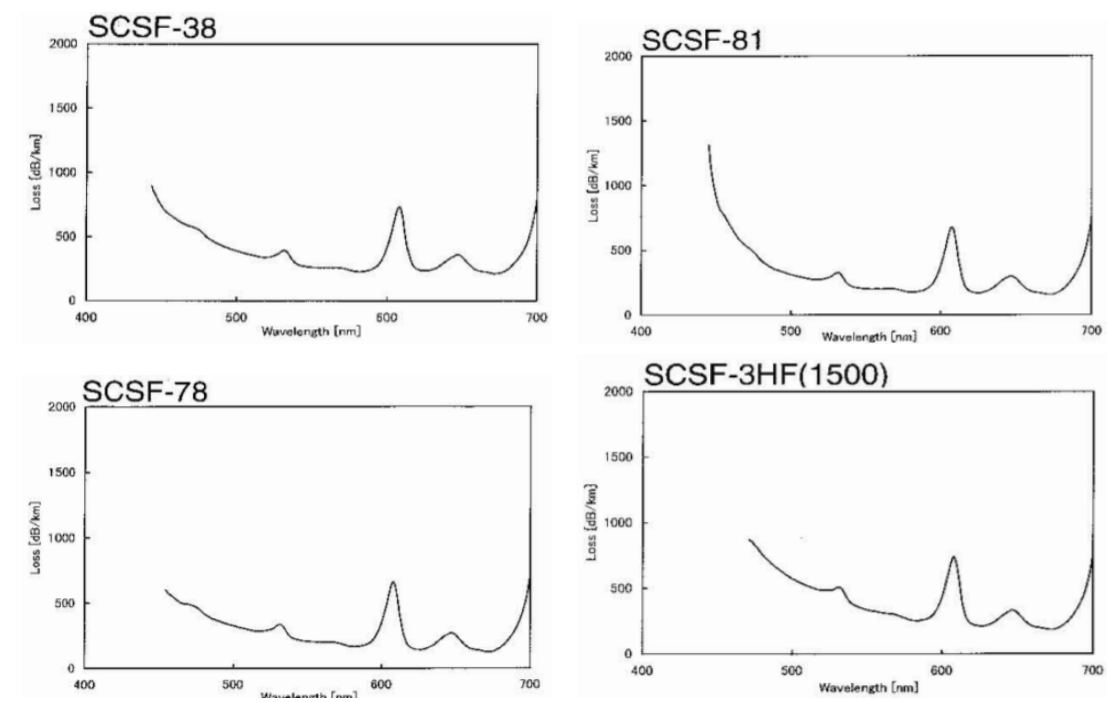




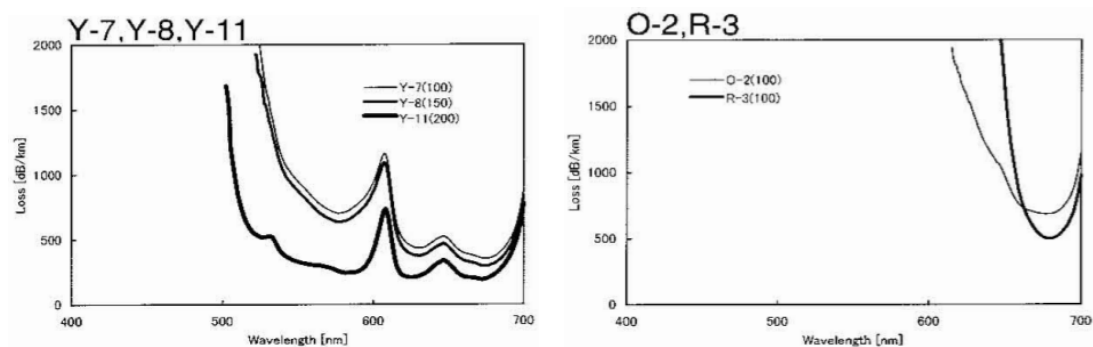
7) The spectra was measured by diluting dye with styrene monomer.

Transmission Loss

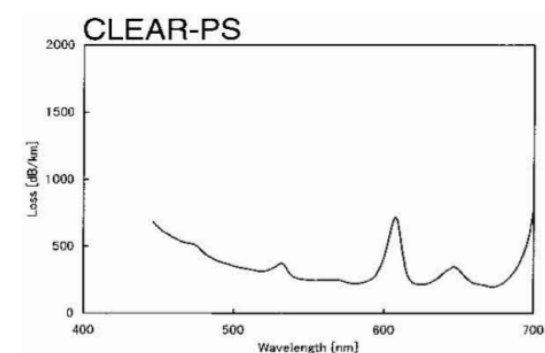
Scintillating Fibers



WLS Fibers



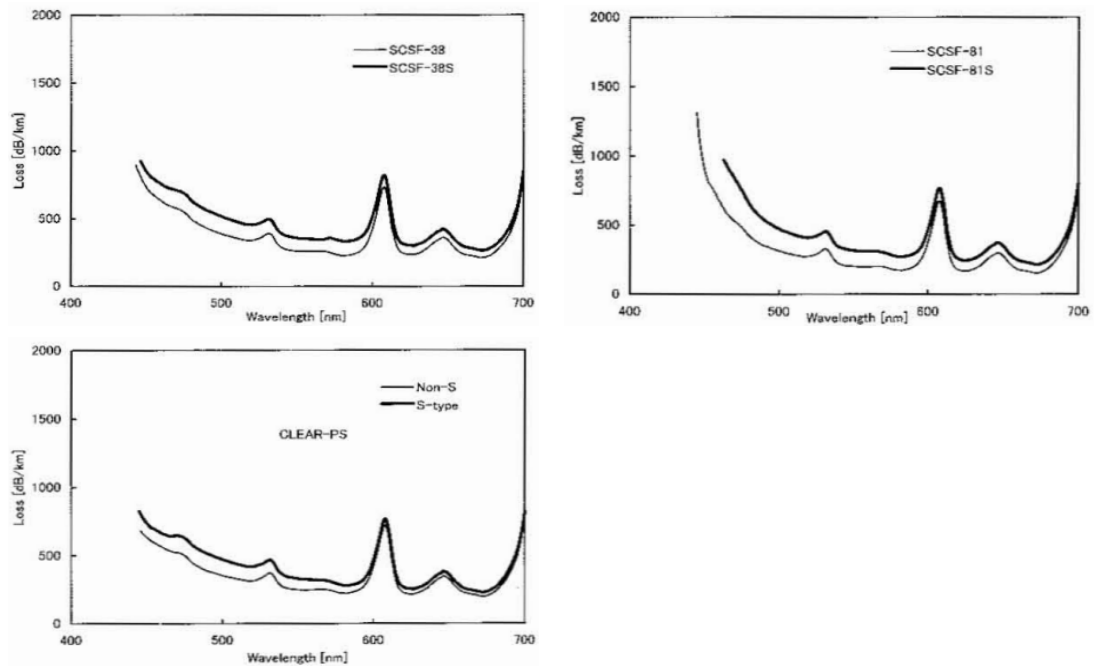
Clear Fiber



Properties of S type Fibers

Attenuation Length

	SCSF-38S	SCSF-81S	SCSF-78S	SCSF-3HF (1500)S	Clear-PSS
Atten. Length (m)	> 2.8	> 3.0	> 3.5	> 4.0	> 8.0



How to Specify Fibers

- In order to specify fibers, the following points must be clarified. - Description, - Cross-section (Round or Square), - Cladding (Single or Multi), - Non-S type or S type, - Length and Dimension, - Cane or Spool, - Concentration of dye must be clarified in 3HF fiber and WLS fibers.

Examples of writing are as follows;

·SCSF-3HF(1500)M, 1.00., 2000m on spools

→ Round fiber, Multi cladding, Non-S type , 1.0mm diameter, 2000m length.

Fiber is put on spool, and the concentration of 3HF dye is 1500ppm.

·Y-11 (200)S, 0.5D., 10000m on spools

→ Round fiber, Single cladding , S type, 0.5mm diameter, 10000m length, put on spools, the concentration of WLS dye is 200ppm.

·Clear-PSMS, 0.83SQ., 3m cane

→Square fiber, Multi cladding , S type, 0.83mm square, 3m length cane.

Features of SCSN

Polystyrene Base

Because of a special method of cross-linking the polystyrene, SCSN plastic scintillators have excellent mechanical properties. (See physical parameters mentioned below.) They are several times easier to form than polyvinyltoluene-base scintillators.

Large Size

SCSN plastic scintillators can be supplied in sizes up to $2400mm \times 1400mm$.

Formulations

Description	Light Output	Peak of Emission	Att.Length ⁸	Decay Time	Softening Point
SCSN-61	55% Anthracene	430nm	0.92m	2.5ns	95°C
SCSN-81	50% Anthracene	440nm	1.40m	2.5ns	95°C

8) Test samples' sizes are 1500mm m $\times$ 50mm $\times$ 10mm.

Otherwise than descriptions mentioned above, various scintillators are available.

Physical Parameters of SCSN and Other Bases of Scintillators

Test Subjects	Tensile Strength (kg/cm ²)	Rockwell Hardness (M-Scale)	Izod Impact Energy (kg)·cm/cm	Deformation Temperature (°C)	Retention of the Bending Strength Against the Radiation(%)	Aging Effect
SCSN	660	81	2.2	95	96	O
Polystyrene	500	84	1.2	82	105	X
Polyvinyltoluene	260	89	1.9	73	89	X
PMMA + 15% Naph	490	64	2.4	55	< 5	-
PMMA	780	100	2.2	100	< 5	O

The fourth item, the deformation temperature, was measured at a maximum stress of 264 psi.

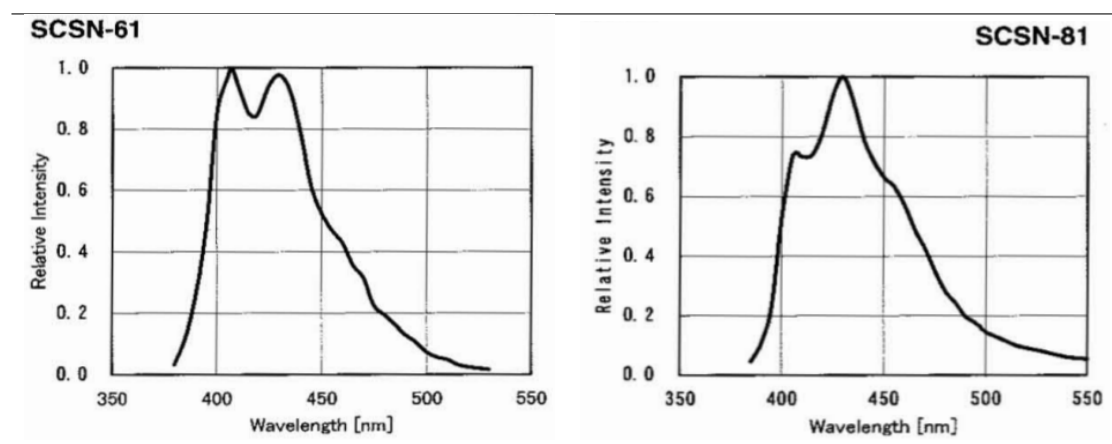
The fifth item, the retention of the bending strength, shows the change after an irradiation of 5×10^7 rad of Co – 60.

The last item, the aging effect refers to the changes appearing in a polished surface after a one week experience of the repetition of 8 hours at 70 °C and 16 hours at

room temperature, in a condition of 100% relative humidity.

O: no remarkable change. X: remarkable change.

Emission Spectra



APPENDIX B

HAMAMATSU H5783 PHOTOMULTIPLIER TUBE

Metal Package PMT

Photosensor Modules H5773/H5783/H6779/H6780 Series



The H5773/H5783/H6779/H6780 series are photosensor modules housing a metal package PMT and high-voltage power supply circuit. The metal package PMTs have a metallic package with the same diameter as a TO-8 package used for semiconductor photodetectors, and deliver high gain, wide dynamic range and high-speed response while maintaining small dimensions identical to those of photo-diodes. The internal high-voltage power supply circuit is also compact, making the module easy to use.

Considering the mounting methods, a cable output type and a pin output type are provided, and a total of 7 types are available according to the wavelength range to be measured. A P-type is also available with selected gain and dark count ideal for photon counting under extremely low light conditions.

Product Variations

Suffix Type No.	None	-01	-02	-03	-04	-06	-20	Output Type	Features
H5773	yes	yes	yes	yes	yes	yes	yes	On-board	Low power consumption
H5783	yes	yes	yes	yes	yes	yes	yes	Cable output	
H5773P	yes	no	no	no	no	no	no	On-board	For photon counting
H5783P	yes	no	no	no	no	no	no	Cable output	Low power consumption
H6779	yes	yes	yes	yes	yes	yes	yes	On-board	Low ripple noise
H6780	yes	yes	yes	yes	yes	yes	yes	Cable output	Fast settling time

Suffix	Spectral Response
None	300 nm to 650 nm
-01	300 nm to 850 nm
-02	300 nm to 880 nm
-03	185 nm to 650 nm
-04	185 nm to 850 nm
-06	185 nm to 650 nm
-20	300 nm to 900 nm

The suffix -06 type (synthetic silica window) has higher sensitivity than the -03 type below 300 nm in wavelength range.

Specifications

Parameter			H5773 / H5783 / H6779 / H6780 Series					Unit	
Suffix			None	-03, -06	-01, -04	-02	-20	—	
Input Voltage			+11.5 to +15.5					V	
Max. Input Voltage			+18					V	
Max. Input Current			H5773 / H5783 Series: 9 H6779 / H6780 Series: 30					mA	
Max. Output Signal Current			100					μA	
Max. Control Voltage			+1.0 (Input impedance 100 kΩ)					V	
Recommended Control Voltage Adjustment Range			+0.25 to +0.9					V	
Effective Area			φ8					mm	
Sensitivity Adjustment Range			1: 10 ⁴					—	
Peak Sensitivity Wavelength			420	420	400	500	630	nm	
Cathode	Luminous Sensitivity	Min.	40	40	80	200	350	μA/lm	
		Typ.	70	70	150	250	500		
	Blue Sensitivity Index (CS 5-58)		8	8	—	—	—	—	
	Red/White Ratio		—	—	0.2	0.25	0.45	—	
	Radiant Sensitivity *1		62	62	60	58	78	mA/W	
Anode	Standard Type	Luminous Sensitivity	Min.	10	10	15	25	35	A/lm
		Typ.	50	50	75	125	250		
	Radiant Sensitivity *1 *2		4.3 × 10 ⁴	4.3 × 10 ⁴	3.0 × 10 ⁴	2.9 × 10 ⁴	3.9 × 10 ⁴	A/W	
	P Type	Dark Current *2 *3	Typ.	0.2	0.2	0.4	2	2	nA
			Max.	2	2	4	20	20	
		Gain *2	Min.	7.5 × 10 ⁵	—			—	
			Typ.	1 × 10 ⁶	—				
		Radiant Sensitivity *1 *2		6.2 × 10 ⁴	—			A/W	
		Dark Count *2 *3	Typ.	80	—			s ⁻¹	
Max.			400	—					
Rise Time *2			0.78					ns	
			H5773 Series	H5783 Series	H6779 Series		H6780 Series		
Ripple Noise *2 *4 (peak to peak) Max.			1.2			0.6		mV	
Settling Time *5			2			0.2		s	
Operating Ambient Temperature			+5 to +50			+5 to +45		°C	
Storage Temperature			-20 to +50					°C	
Weight			60	80	60		80	g	

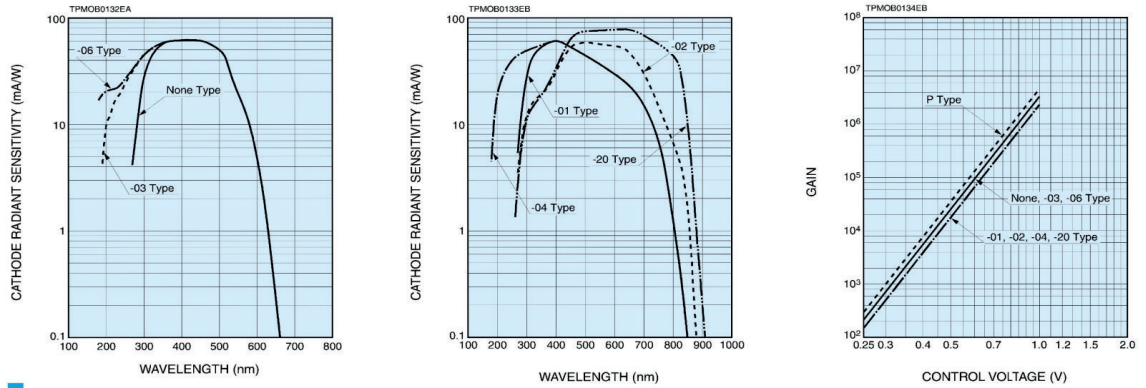
*1: Measured at the peak sensitivity wavelength *2: Control voltage = +0.8 V *3: After 30 minute storage in darkness

*4: Cable RG-174/U, Cable length 450 mm, Load resistance = 1 MΩ, Load capacitance = 22 pF

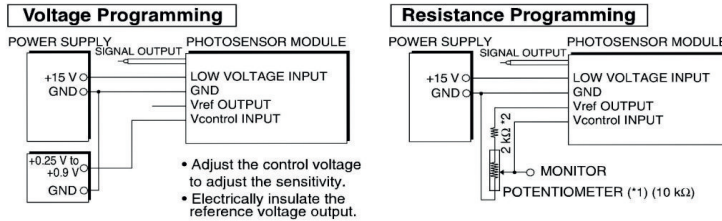
*5: The time required for the output to reach a stable level following a change in the control voltage from +1.0 V to +0.5 V.

Current Output Type Photosensor Modules

Characteristics (Cathode radiant sensitivity, Gain)

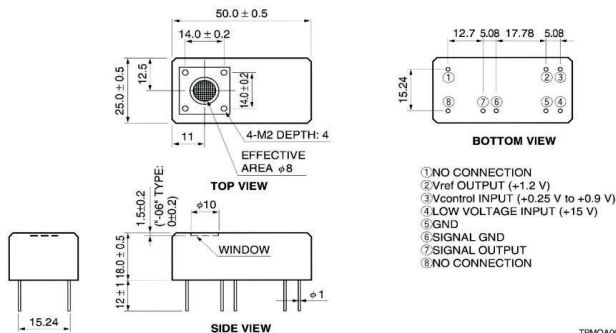


Sensitivity Adjustment Method

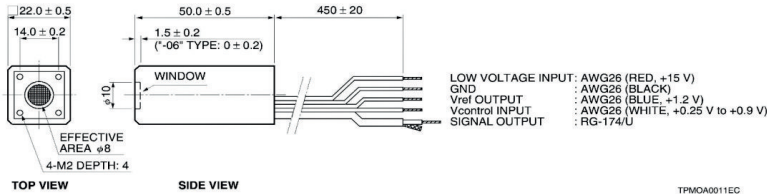


Dimensional Outlines (Unit: mm)

H5773/H6779 Series

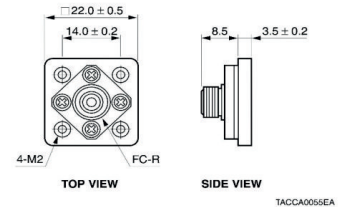


H5783/H6780 Series



Option (Optical Fiber Adapter) (Unit: mm)

E5776 (FC Type)



E5776-51 (SMA Type)

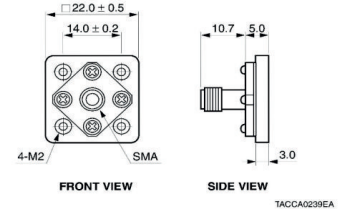


Figure B.1: Data sheet of Hamamatsu H5783 Photomultiplier tube used in this thesis.