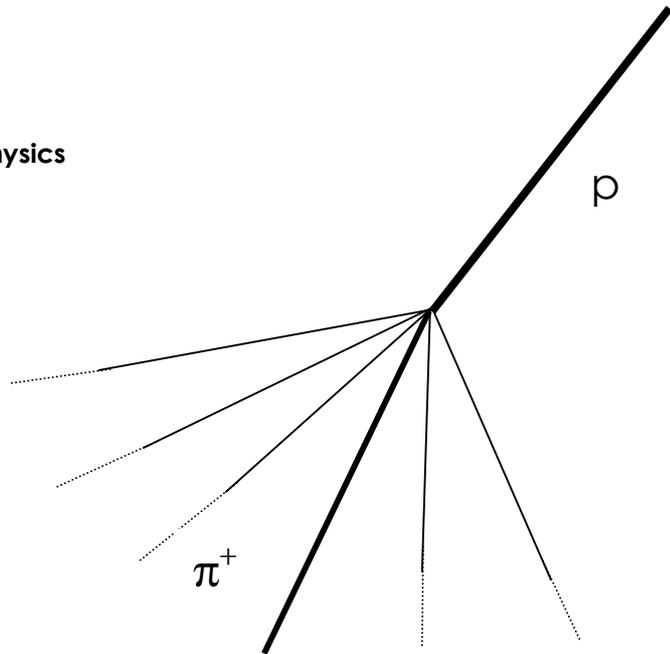KUNGL
TEKNISKA
HÖGSKOLAN

VETENSKAP
OCH
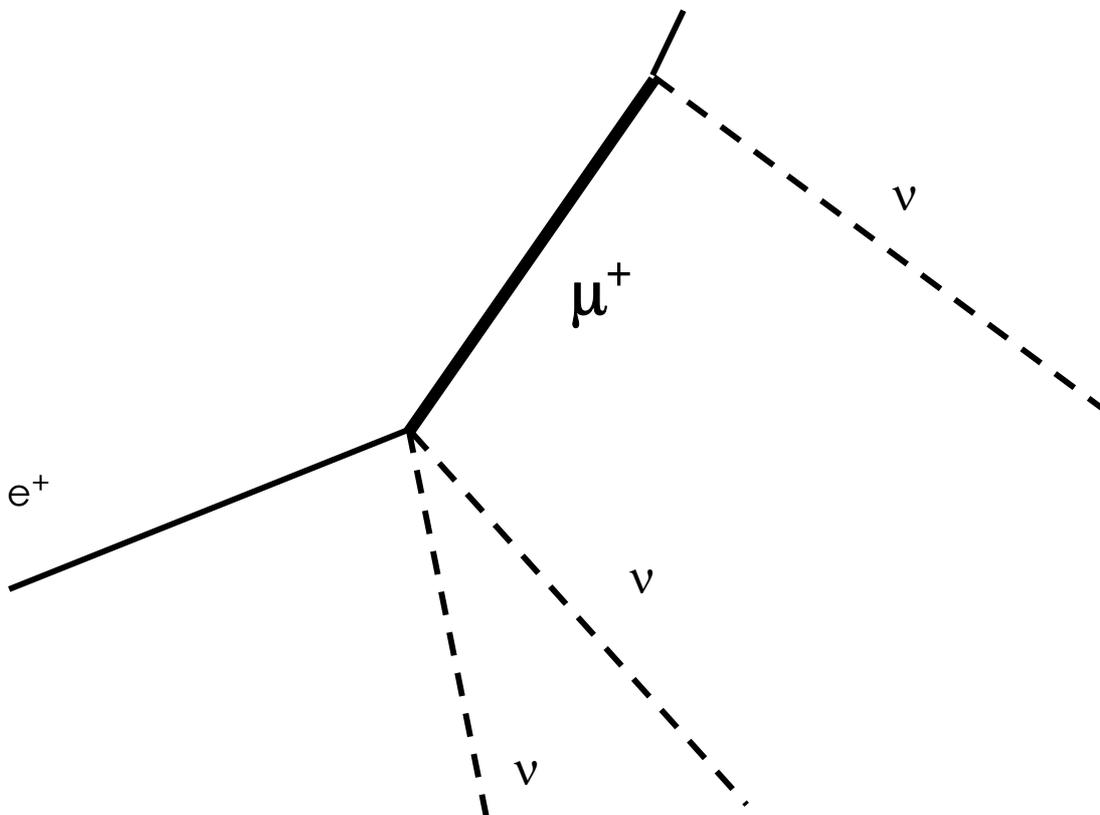KONST

**Section of Experimental Particle Physics**

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Version 3

p

$\pi^+$

# Measuring the Lifetime of Cosmic Ray Muons

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$\nu$

$\mu^+$

$e^+$

$\nu$

$\nu$

## Introduction

The purpose of this laboratory is to measure the lifetime of cosmic-ray muons. The experimental technique is straight-forward. Cosmic ray muons are stopped in an aluminium target which is sandwiched between plastic scintillator detectors:



*Cosmic-ray muon ($\mu^+$ or $\bar{\mu}$)*

*Aluminium target*

*Scintillator detector*

*Decay $e^+$ or $e^-$*
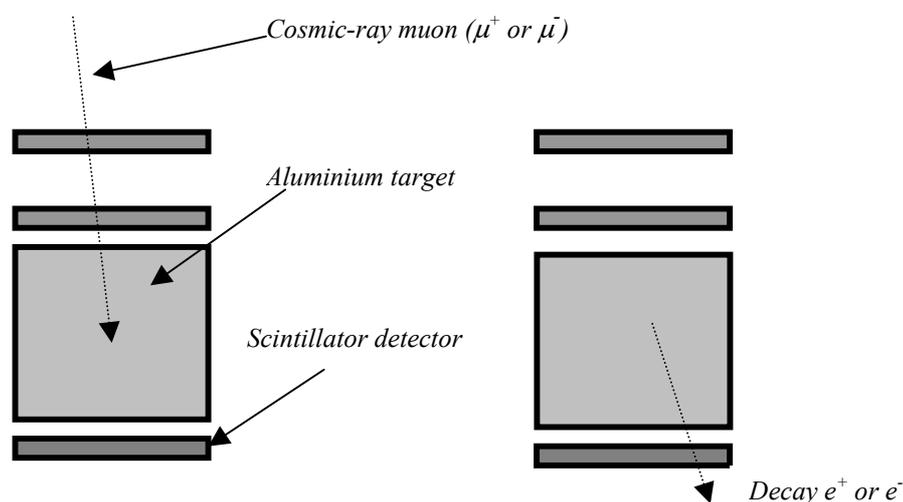
A stopping muon is indicated by a signal in the top and middle scintillators but no signal in the bottom scintillators. The time between the muon stopping and its decay (a further signal in the middle or bottom scintillator) is measured with an electronics system. The muon lifetime can then be extracted from the exponential distribution of decay times which are recorded.

During the course of the laboratory, you will:

1. Build your own scintillator detector and investigate its performance with a radioactive source and cosmic rays.

2. Make a preliminary measurement of the muon lifetime from data taken during the laboratory and compliment this with a more precise measurement from data recorded during a longer data-taking run.

**Your understanding will be checked as the lab progresses by questions highlighted in italics through-out the script – there is no project report to write. However, before attending the laboratory you are expected to prepare yourself by answering the eight questions appended to the end of this script.**

## Theory and Background

### Historical interlude

In the mid-1930's, physicists had a fairly simple view of the structure of matter. The building blocks were the proton, the electron and the neutron. Three other particles were known or had been postulated at the time: the photon, the neutrino, and the positron. These six particles were considered the fundamental constituents of matter. With this marvelously simple picture of the world, however, no one could provide an

answer to an important question: since the protons inside a nucleus should strongly repel each other because of their like charges, what is the nature of the force that holds the nucleus together? Scientists recognized that this mysterious force must be much stronger than anything encountered in nature up to that time.

In 1935 the Japanese physicist Hideki Yukawa (1907-1981) proposed the first theory to successfully explain the nature of the nuclear force, an effort that later earned him a Nobel prize in physics. To understand Yukawa's theory, it is useful to first recall that in the modern view of electromagnetic interactions, charged particles interact by exchanging photons. Yukawa used this idea to explain the nuclear force by proposing a new particle whose exchange between nucleons in the nucleus mediates the nuclear force. Furthermore, he established that the range of the force would be inversely proportional to the mass of the mediating particle and predicted that its mass would be about 200 times the mass of the electron. Since the new particle would have a mass between that of the electron and that of the proton, it was called a meson (from the Greek meso, 'middle').

In an effort to substantiate Yukawa's predictions, physicists began an experimental search for the meson by studying cosmic rays entering the Earth's atmosphere. In 1937 Carl Anderson and his collaborators discovered a particle of mass 106 MeV, about 207 times the mass of the electron. However, a subsequent experiment showed that the particle interacted very weakly with matter and hence could not be the carrier of the strong force. The puzzling situation inspired several theoreticians to propose that there were two mesons with slightly different masses. This idea was confirmed by the discovery in 1947 of the $\pi$ meson, or simply pion, by Cecil Frank Powell (1903-1969) and Giuseppe P.S. Occhialini (1907- ). The particle discovered by Anderson in 1937 was not a meson as it takes part in the weak and electromagnetic interactions only. This particle is now called the muon.

The pion, Yukawa's carrier of the nuclear force[a], comes in three varieties corresponding to three charge states: $\pi^+$, $\pi^-$ and $\pi^0$. The $\pi^+$ and $\pi^-$ particles have masses of 139.6 MeV, while the $\pi^0$ has a mass of 135.0 MeV. Pions and muons are very unstable particles. For example, the $\pi^-$, which has a mean lifetime of $2.6 \times 10^{-8}$ s, first decays to a muon and muon antineutrino. The muon, which has a lifetime of $2.2 \times 10^{-6}$ s, then decays to an electron, a muon neutrino, and an electron antineutrino, thus :

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$
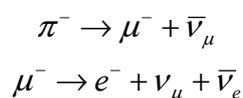
### *Cosmic ray muons*

Muons are unstable elementary particles, which have a charge equal to that of an electron and a mass 207 times that of the electron. Muons can be produced by the collision of cosmic radiation with atoms high (10 km) in the atmosphere. Muons have a lifetime of 2.2µs when measured in a reference frame at rest with respect to them. Given this muon lifetime and assuming a velocity close to that of light, we would find that muons could only travel a distance of about 650 m before they decayed. Hence,

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[a] Nowadays, it is well known that the gluon is the quanta of the strong interaction and Yukawa's theory should be considered as an effective theory for low energies.

they could not reach the Earth from the upper atmosphere where they are produced. However, experiments show that a large number of muons do reach the Earth. The phenomenon of time dilation explains this effect.

Time dilation:

$$t = \frac{t'}{\sqrt{1 - \dfrac{v^2}{c^2}}} = \gamma t',$$

(where t is a time measured in the laboratory system, t′ is the time measured in the rest frame of the system, v is the velocity of the system and c is the speed of light) is a very real phenomenon that has been verified by various experiments. Relative to an observer on Earth, the muons have a lifetime equal to $\gamma\tau$, where $\tau = 2.2\mu s$ is the lifetime in a frame of reference traveling with the muons. For example, for v = 0.99c, $\tau = 7.1$ and $\gamma\tau = 16\mu s$. Hence, the average distance traveled as measured by an observer on Earth is $\gamma\tau v = 4700m$.

In 1976, experiments with muons were conducted at the European Particle Physics Laboratory (CERN) in Geneva. Muons were injected into a large storage ring, reaching a velocity of about 0.9994c. Electrons produced by the decaying muons were detected by counters around the ring, enabling scientists to measure the decay rate, and hence the lifetime of the muons. The lifetime of the moving muons was measured to be about 30 times as long as that of the stationary muon, in agreement with the prediction of relativity to within two parts in a thousand.

### The production of cosmic-ray muons

Cosmic ray particles hit the Earth's atmosphere at the rate of about 1000 per square meter per second. They are composed of nuclei (about 90% protons, 9% alpha particles and the rest heavier nuclei) and electrons. Most cosmic rays are relativistic, having energies comparable to their masses. A small fraction of them have ultra-relativistic energies extending up to $10^{20}$ eV (about 20 Joules), eleven orders of magnitude greater than the equivalent rest mass energy of a proton.

The most important sources of cosmic ray muons are from charged pion and kaon decays:

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$
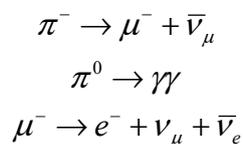
Muons have a small cross section for interactions, so they are very penetrating. They are often referred to as minimum ionizing particles (m.i.p.). However, because they are charged, they are easy to detect. The momentum spectrum for muons at sea level is shown below. The solid line is a parameterisation of the high energy points and can be ignored.

Intensity (cm² s sr (GeV/c))⁻¹ versus Muon Momentum (GeV/c)
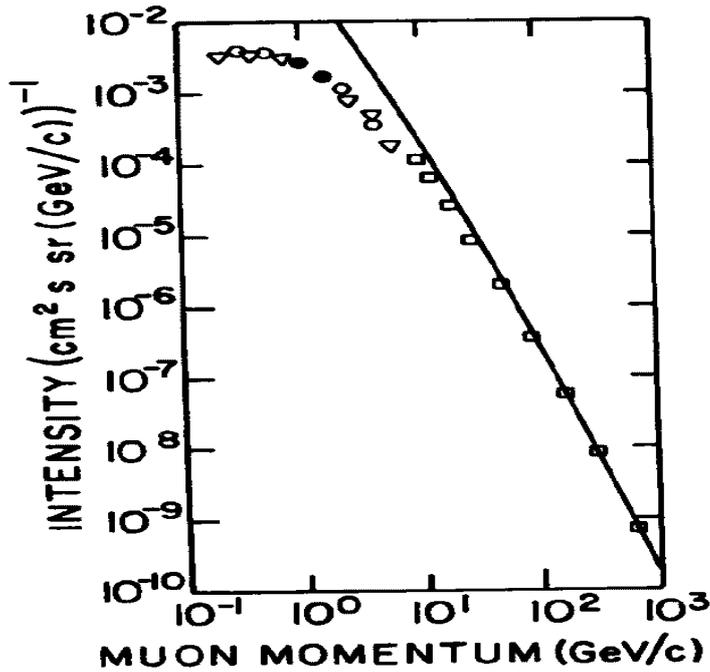
### Energy loss processes for muons

Energy loss processes for muons with energies relevant to this experiment are dominated by ionization of the medium through which the muon passes. The rate of energy loss (often called dE/dx) is almost constant for relativistic particles, with the magnitude depending somewhat on the medium. The energy loss rate for relativistic muons has a broad minimum (approximately 1.8 MeV/(g/cm$^2$) in rock) below 1GeV and rises slowly at higher energies.

Finally, muons can experience another form of interaction depending on their charge. Positive muons can form 'muonium' which is a bound state of a positive muon and an electron – in an analogous fashion to the bound $e^+e^-$ state called positronium. Negatively charged muons can take the place of a electron in the outer orbital of an atom forming a muonic atom. Since the muon has 207 times the mass of an electron, the radius of the muon orbit is much smaller than the corresponding radius for a electron.

### The Lifetime of the muon

Stationary muons do not all live for the same amount of time – there is an intrinsically random element in the decay process. It is not possible to calculate the lifetime of a given muon, rather we are able to calculate the average lifetime of a large collection of muons. Since elementary particles are not endowed with a memory, the probability for a given muon to decay in given time period is completely independent of how long ago the muon was created. This is in stark contrast to a biological system, where an 90 year old person is more likely to die (decay !) next year than a young person in the coming year.

Assume we have a large number of muons, N(t), at a given time, t. If we define a parameter, $\Gamma$, to be the decay rate (probability per unit time that a given muon will decay), then $N \Gamma dt$ muons will decay in a time dt, i.e.:
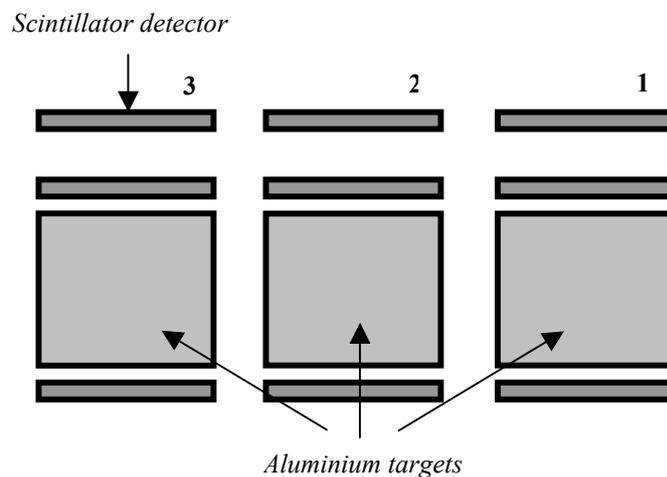
$$dN = -\Gamma N dt$$

And so it follows that:

$$N(t) = N_0 e^{-\Gamma t}$$

The number of muons remaining in the sample is decreasing exponentially with time and it is usual to express the lifetime, $\tau$, of the sample as $\tau = 1/\Gamma$.

## The Experimental Set-up

The following figure shows the layout (not to scale) of the scintillators and aluinium targets used to measure the muon lifetime (as from 2003, only two units are used):



Each scintillator is connected to a photomultiplier tube and electronics system which is described below. The scintillators were recovered from an experiment at CERN, called CP-Lear. They are 1.5m long, 3cm thick and 12cm wide. The scintillators are arranged into 3 modules. Each module is an exact copy of its neighbour and modules are operated in parallel to speed up data taking. All modules have aluminium targets with a square cross-section, of side 10cm.

## The Electronics Set-up

An overview of the electronics set-up for one scintillator is given in the diagram below:
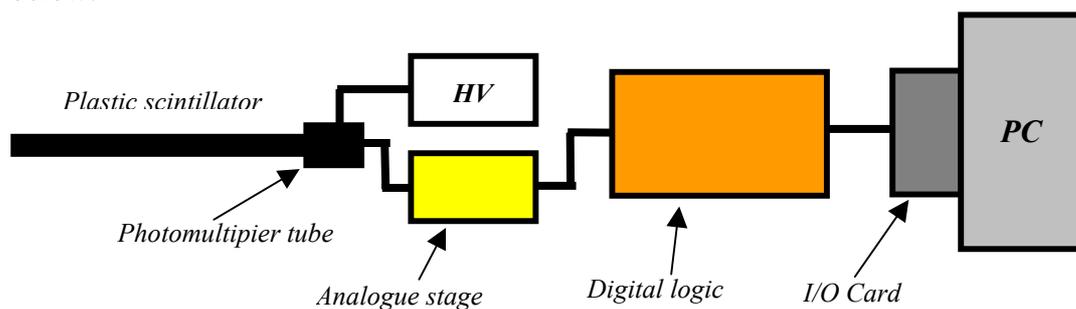
## High Voltage Supply

In preparation, read chapter 8 of 'Techniques for Nuclear and Particle Physics Experiments' by W.R. Leo (2$^{nd}$ edition, Springer-Verlag 1994) on Photomultipliers.

Each photomultiplier tube needs increasingly higher voltage potentials on successive dynodes in order to accelerate and guide the electron beam originating from the photocathode in an efficient manner. This is done by voltage dividers built up by a resistor chain as illustrated by the following schematic:

Photomultiplier socket connecting to dynodes.

Output connector

HV input
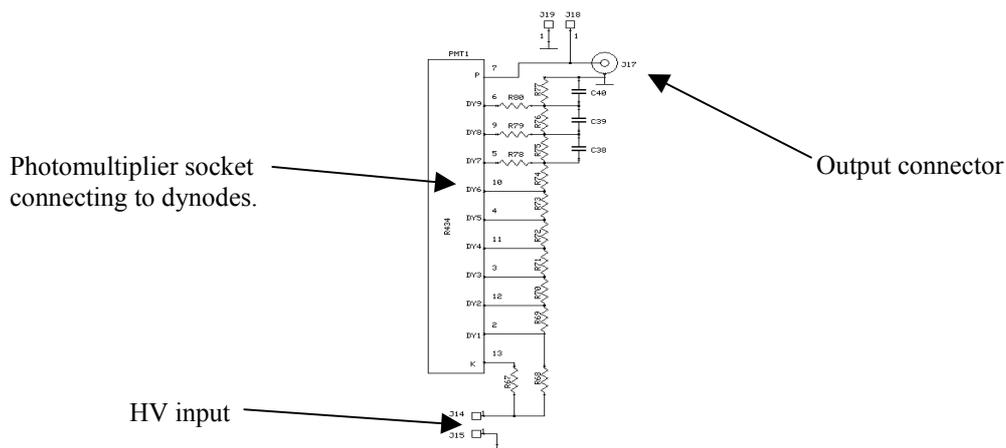
A constant current is flowing through the resistor chain, keeping the dynodes at a constant potential as long as the electron beam current in the photomultiplier tube is low. The capacitors over the last dynodes are used as charge buffers to maintain a constant potential on the last dynodes even in the presence of relatively high currents.

Normally, the entrance window (cathode) is kept at a negative high voltage potential and the anode is kept at ground to simplify the design of the subsequent analogue electronics which is connected to the anode. **This implies that one should exercise extreme caution when handling a photomultiplier tube when the high voltage is on, since the inside of the entrance window is held at a high voltage**.

## Analogue Electronics

The analogue electronics is implemented in the so-called NIM standard. This is a widely used standard in particle and nuclear physics, where electronics modules with different functions are placed in a metal box (usually called a 'crate'). To make the circuit you need, its simply a case of choosing the correct modules and connecting them together. This system is optimized for dealing with the fast pulses often experienced in particle physics and nuclear physics.

A photomultiplier tube is a true current generator (*do you understand why?*). In order to detect the current pulse, the output of the photomultiplier tube is normally connected to ground through a resistor, giving a voltage pulse across the resistor. The purpose of the analogue electronics is to convert this small amplitude voltage pulse into a signal which is suitable for the following digital electronics stage. Each photomultiplier tube is connected to a separate analogue circuit. The digital

electronics expects an industry standard TTL (Transistorised Transistor Logic) pulse of 5 V amplitude each time there is a light pulse in the scintillator.

Three different types of NIM module are used to achieve this:

1. Amplifier
2. Discriminator
3. NIM to TTL converter

You will study the purpose and behaviour of these modules during the laboratory exercise.

### Digital Electronics, Data Acquisition and Processing

The digital TTL output pulses from the photomultiplier system to the Altera circuit board. The two key components on the circuit board are an Altera FLEX 10K20 programmable logic device (PLD) and a 25.175 MHz crystal oscillator. The positioning of the important components on the circuit board is shown below.
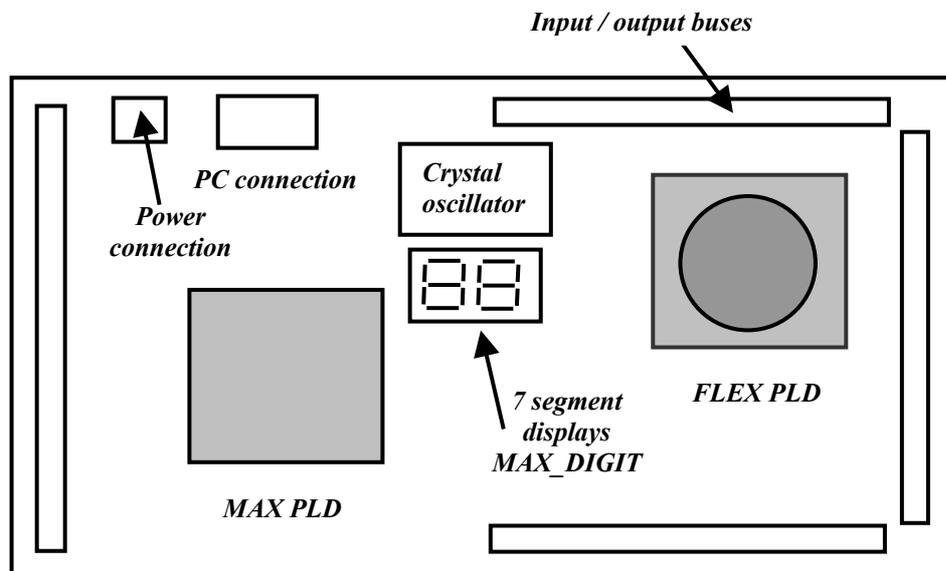


The purpose of the digital electronics is threefold:
1. Decide (with digital logic implemented on the PLD) when a muon has come to rest in one of the aluminium targets and start a fast clock (provided by the crystal oscillator).
2. Stop the clock when the decay electron or positron is detected.
3. Pass the time and information on which scintillators were triggered onto the PC before resetting the electronics in readiness for the next stopping muon.

### Programmable Logic Devices (PLD's)

PLD's are extremely flexible and powerful state-of-the-art electronic components. Basically, a PLD is a programmable device which can be configured to behave like any digital device or circuit. A single PLD can therefore replace a whole circuit board

of digital chips – ask to see some old prototypes of the muon lab electronics for proof of this! Many PLD's (including the one which you will use) can be reprogrammed from a computer which means that designs can be debugged and revised very simply and cheaply. Note that you may also see PLD's referred to as Field Programmable Gates Arrays (FPGA's) and Programmable Logic Arrays (PLA's) in other literature – the choice of name tends to vary from manufacturer to manufacturer. A PLD typically contains an array of logic elements such as gates, flip-flops and registers with programmable internal interconnections between the different elements. Nowadays, these reprogrammable interconnections are controlled by Complementary Metal Oxide Silicon (CMOS) switches controlled by Static Random Access Memory (SRAM). The Altera FLEX 10K20 PLD has an equivalent capacity of approximately 20000 logic gates (AND, OR, NOT etc.) and can therefore be used in very advanced designs. The (unoptimised) design file for the muon lab occupies approximately 5% of the space available within in device! The circuit board also holds a less performant PLD which has a capacity of approximately 2500 logic gates.

A suite of software programs called MAX+plusII is offered by Altera to allow their PLD's to be programmed very easily. There are four main parts to implementing a design on the PLD :

1. *Design Entry.* For the muon lab, the design was programmed graphically, although text-based hardware description languages are also popular. The overall graphical design file for a one module version the muon lab is shown in appendix B.
2. *Simulation.* The software also allows designs to be fully simulated before they are transferred to the PLD. This speeds the design process substantially as one does not need access to the digital photomultiplier signals in order to check that the digital electronics works as planned.
3. *Compilation.* Just like any programming environment, the design code must be compiled and programming errors located. The compiler also checks that the design will fit into the PLD and that basic design rules have not be ignored.
4. *Programming.* A cable running from the PC's parallel port connects to the Altera circuit board and allows data to be transferred directly to the SRAM switches of the PLD.

### Data Acquisition and Processing

A standard PC is used to process the data from the Altera board. The interface to the board is provided by commercial digital Input/Output (I/O) cards mounted on the PC's PCI bus. LabView Software from National Instruments is used to read the I/O cards. LabView is a graphical programming language which allows complex data acquisition and processing systems to be efficiently implemented. For this laboratory, the LabView code looks for changes on the I/O port which indicates that a stopped muon has been identified by the Altera. A 9-bit counter on the PLD (indicating the time between a start and stop signal) is then read and the time stored along with a bit-pattern indicating which scintillators were triggered. This information can be used to make sure events have the correct topology, ie: a start and stop signal from the same module. When the information has been stored and the on-screen histogram updated a reset is sent to zero the counter and scintillator bit-pattern. The overall graphical code for the muon lab is shown below with annotations (much of the complexity is hidden in nested frames!).
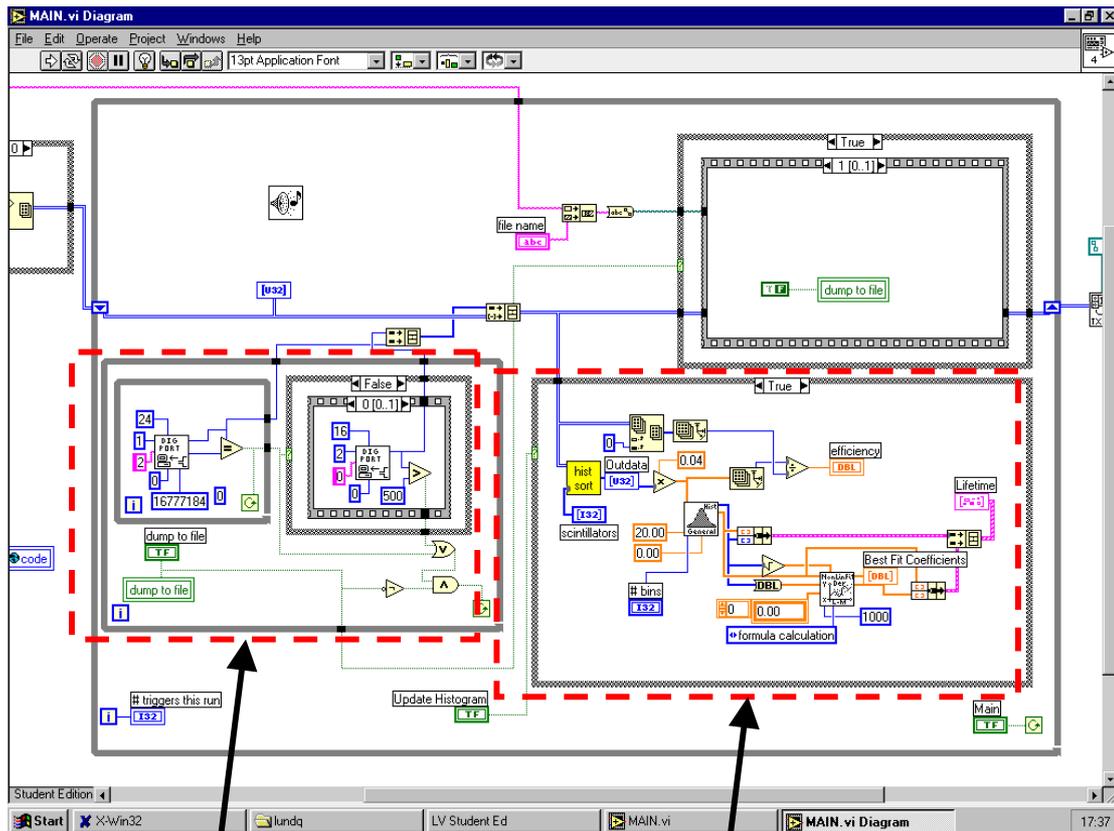
*Loop for reading the digital port on the I/O card*

*Histogramming the data every time a muon decay is seen*

## Laboratory Activities with Questions

There are three laboratory activities, labeled (A) to (C).

### (A) The very first thing to do!

Right at the start of the lab be sure to activate the LabView program and start to collect data. Towards the end of the lab you will use this data to make a preliminary measurement of the muon lifetime. The front-panel for the LabView program is shown in appendix C.

### (B) Build your own scintillator detector and study it's performance

In this part of the lab you will build and test your own scintillator detector. In preparation, read chapter 9 of 'Techniques for Nuclear and Particle Physics Experiments' (W.R. Leo, 2<sup>nd</sup> edition, Springer-Verlag 1994) on 'Scintillation Detector Mounting and Operation'.

1.  Wrap the scintillator in aluminium reflecting material to maximize the light output from the scintillator. Leave a hole at one end.

2. Seal the scintillator with black tape to exclude external light.
3. Attach the scintillator to the photomultiplier tube using coupling grease to get a good optical contact, and fix it with more black tape at the base.
4. Mount the photomultiplier tube in the high voltage divider if needed.
5. Connect the high voltage (**ask for help – the operating voltage is 800V**) and look at pulses from your scintillator detector with the oscilloscpe. Study the output with cosmic rays or a $^{137}$Cs source. The source is not dangerous, but should be handled carefully at all times and returned to the lead 'coffin' when not in use.

⇒ *Why are the amplitudes of the output pulses different for the 660 keV gamma rays from $^{137}$Cs and for cosmic rays?*

6. Study the analogue circuitry. Connect the output of your scintillator to the first NIM module (amplifier). **Do not unplug any cables already in place!** Study the output with the oscilloscope. Then, add the other NIM modules in the correct order and study their outputs. Use more than one channel of the oscilloscope, so that you can study correlations between the signals. This part of the laboratory is deliberately vague… use your imagination!

⇒ *Explain what the purpose of each NIM module is and how they can be used together to identify muons passing your scintillator.*

## (C) Measure the muon lifetime

This exercise has two parts. In the first part you will make a preliminary analysis of the data you have been collecting with the muon lab since the start of the laboratory. In the second part you will be given access to data from a much longer data-taking run so that you can make a more precise measurement.

*Part one*
1. Stop the Labview program running and note down the file name that the data was saved to.
2. Minimise all the Labview windows.
3. Make sure a small icon of a terminal with an 'X' on the screen appears in the icon tray. If its missing ask your lab assistant for help.
4. Double-click on the 'SSH Secure Shell Client'. From the 'profiles' tab, choose 'muonlab'. **Ask the lab assistant for the password**. This connects you to one of the powerful Linux work stations in the particle physics group. You'll use this computer for your data analysis.
5. Type: [export DISPLAY='130.237.70.128:0.']. This allows you to send windows from the Linux workstation to the PC.
6. Once logged in type [cd muonlab] and then [cd 200n] to change directory to where the analysis software is located. NB: substitute the current year for 'n'.
7. You must now transfer your data file from the PC to the Linux workstation. Within the Secure Shell Client, choose the 'Window' menu and 'New File Transfer'. A new window should appear showing the muonlab directory on the workstation. Double-click on 'muonlab' and then '200n'. This is the directory where you'll put your data file.

8. Select the 'operation' menu and then 'upload'. Double-click on the 'muonlab' icon and then the 'data' icon. Locate your file and double-click on it to transfer the file.

9. You'll use a program called PAW (Physics Analysis Workstation) to analyse the muon lab data. This is a standard particle physics analysis program, developed at CERN. The program has been around for many years - so you have to use FORTRAN for programming. A newer development of PAW aimed at the forthcoming LHC experiments uses C++. From the Secure Shell window, type [xterm &] to open a new window and from this window type [paw] to start PAW running. A graphics window labelled 'HIGZ_01' should appear, once you press [return].

10. Note that there is a netscape shortcut to the PAW manual on the PC's desktop.

11. In the Secure Shell window type 'emacs analyse.kumac &' (this is the PAW commands macro file) and then 'emacs f.for &' (this is the function you'll fit to the data). To understand what these files do, read the comments!

12. Emacs is a standard UNIX editor which you may have already encountered. If not, all you need to know is that [control-x-s] (ie: type [x] then [s] while holding down the control key) saves a file to disk!

13. To read your data into histograms which PAW can work with you must type [analyse 1] within PAW. You will be prompted for a file name and the number of entries in the file to be analysed. The easiest way to find the number of lines in a file within UNIX is to type 'wc mydata.dat' at the command prompt. The first number returned is the number of lines in the file. You will also be asked to choose the number of 'bins' in the histograms.

14. Now you can fit your data with a suitable function. In the example code an unrealistic polynomial function is provided - do not use this - choose something more suitable! When you are happy with your code both in the kumac file and the fitting function type [analyse] to run fit the histogram of decay times. Hint: you must account for so-called background events, where for example one muon generates a 'start' signal and another independent muon generates a 'stop'.

⇒ *What function do you need to use to fit the distribution of decay times?*
⇒ *What lifetime do you extract? Hint: the data is histogrammed as clock counts, where the clock frequency on the Altera board is 25.175MHz.*
⇒ *What does the $\chi^2$/ndf (pronounced chi-squared per number of degrees of freedom) figure quoted on the fit mean?*

*Part two*

1. Repeat the above exercise, but this time use a much larger data-file which was accumulated over many days of running. The name of this file is 'all_data.dat' and it contains 117888 entries accumulated over approximately two weeks of continuous running.

⇒ *Fit your single exponential function once again.*

$\Rightarrow$ *Compare the error on the fitted lifetime to the previous value.*
$\Rightarrow$ *What is the $\chi^2$/ndf value?*
$\Rightarrow$ *What is the physical significance of this?*
$\Rightarrow$ *Can you work out how to improve your fit?*

## Home Assignment Questions

The following questions should be answered before you come to do the laboratory exercise.

1. How are cosmic ray muons produced?
2. Why are there so few pions in the cosmic radiation which reaches the Earth ?
3. Most of the cosmic ray muons are produced 10 km up in the atmosphere. Work out the probability that a muon with a momentum of 1 GeV will reach the Earth.
4. How do muons decay?
5. Calculate the Bohr radius for a $\mu^-$ which comes to rest in aluminium. Compare this to the radius of an aluminium nucleus and the first Bohr radius for an aluminum atom. What do you notice?
6. To produce one photon in a plastic scintillator requires 100 eV of energy. Estimate how many photons are produced when a minimum ionising muon traverses a 3cm thick scintillator.
7. Calculate the energy lost by a muon with an initial energy of 200 MeV when it passes through 20 cm of concrete.
8. Calculate the minimum energy a muon must have in order to pass through 10cm of aluminium.
9. Briefly describe how a photomultiplier works.

# Appendix (A)

### *The electronics set-up*

Altera digital electronics board                                                    NIM 'crate'
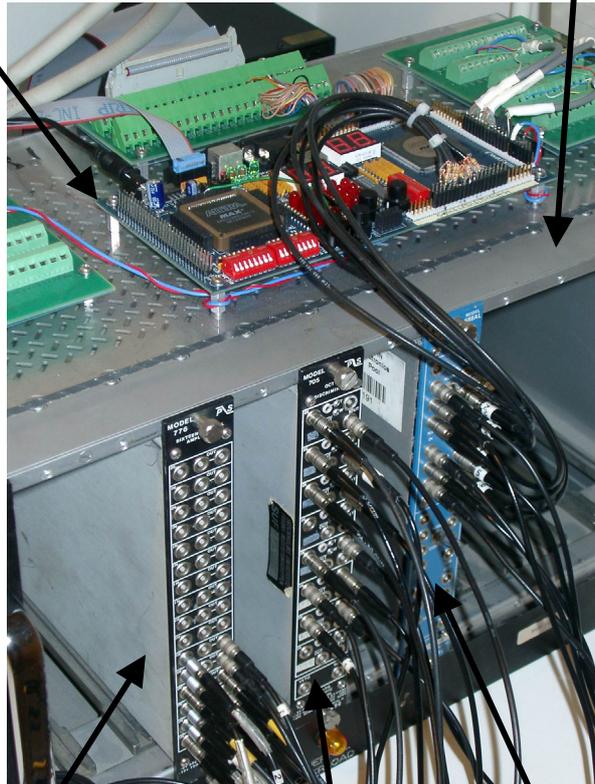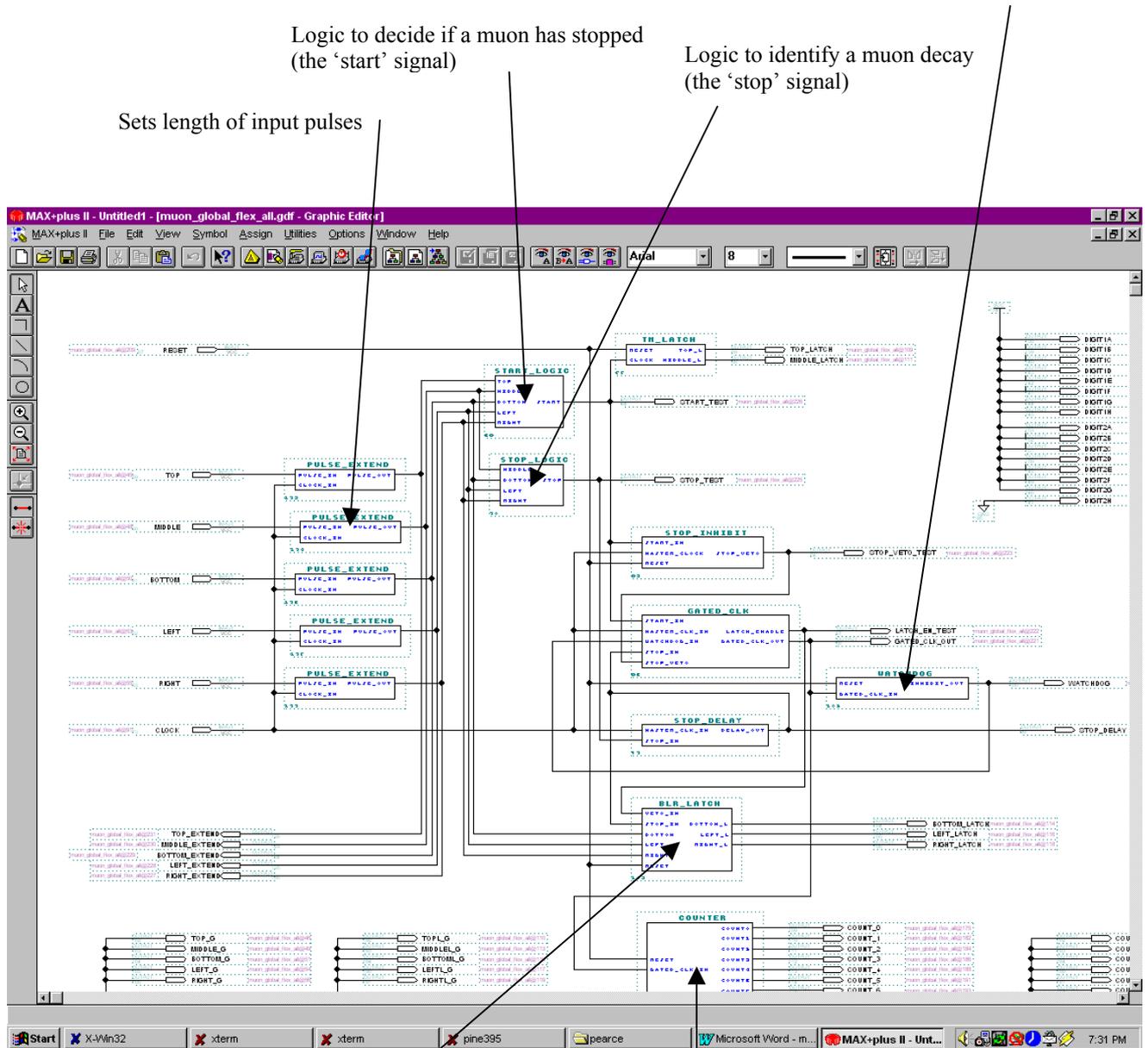


Amplifier module          Discriminator module          NIM-to-TTL module
                                                                    (NB: different colour as from 2003!)

# Appendix (B)

## *The layout of a one module version of the Altera code*

'Watchdog' process to reset everything if no muon decay is seen within 20 μs.

Logic to decide if a muon has stopped (the 'start' signal)

Logic to identify a muon decay (the 'stop' signal)

Sets length of input pulses



Produces scintillator bit pattern for PC

Counter to measure time between a 'start' and 'stop' signal

# Appendix (C)

## *The front-panel of the Labview program*

*Start*   *Stop*   *Decay time histogram*   *Type file name here*