Cosmic rays and the muon lifetime[1]

Abstract

An experiment detecting the decay of cosmic muons has been installed for the third-year students at the University of Lund. The setup of the experiment makes it possible to measure the lifetime of the muon.

A useful source of information is the particle data group web page:
`http://pdg.lbl.gov/`.

Updates and tips will be posted on the muon lab web page:
`http://www.hep.lu.se/muonlab`.

Supervisor:

Oleksandr Viazlo
oleksandr.viazlo@hep.lu.se

Office: C368

[1]Written by Ulrik Egede, Gösta Gustafson, Christina Zacharatou Jarlskog, Janus Schmidt-Sørensen, and modified by Sakar Osman and Eva Haslum (April 2005)

Contents

1 Aims and Goals

The high energy particles studied in this lab are so called cosmic muon, i.e. muons created in the earths atmosphere as it is hit by cosmic rays. Your task will be to measure the muon lifetime.

Aim The aim of the Muon lab is to give you an introduction to experimental methods in high energy physics, by providing an overview of relevant fields of work.

Goals During your work with this lab you are expected to:

1. Familiarize yourself with the detectors and electronic components used in the lab, as well as principles for logical circuits.
2. Use histograms for data storage.
3. Familiarize yourself with tools for data analysis.
4. Describe the underlying physics; how muons are created in the atmosphere and how they decay, properties of the particles involved.
5. Exercise your ability to design an experiment that produces high quality relevant information.
6. Analyze and present results in a scientifically correct way.
7. Compare experimental results with theory and find main differences.
8. Discuss error sources and reliability of the results.

Examination There are two parts to this lab.

A You are given a set of questions to be answered during the lab and analysis sessions.

B During the analysis session you are expected to produce a correct graphical representation of your experimental results, and use those results to determine the muon lifetime.

Upon completion of these tasks, hand in a short lab report where you attach the question sheet from part A as an appendix. Write concisely and to the point - **The lab report should not exceed 5 pages!**

2 Introduction

In this lab, we detect cosmic muons and their charged decay products, electrons and positrons. The aim of the lab is to measure the muon lifetime, i.e. the average duration of the life of a muon in its rest-frame.

3 Origin of the muons

In this experiment, we observe cosmic muons. Cosmic rays are high energy particles produced in the sun and in supernovae and neutron stars of our galaxy. About 85% of the cosmic rays are protons and 12% are alpha particles (helium nuclei). The remainder are electrons and nuclei of heavier atoms. The cosmic rays travel in the space between the stars. In their path they interact with atomic nuclei and they produce new cosmic rays, like antiprotons, positrons, photons and neutrinos. The cosmic rays that reach our atmosphere are called primary cosmic rays. The energy spectrum of primary cosmic rays, i.e. the number of particles as a function of energy, has been measured over an enormous range. For the nuclear component, it is shown in Figure 1. A good fit to the data, except at the lowest energies, is the following:

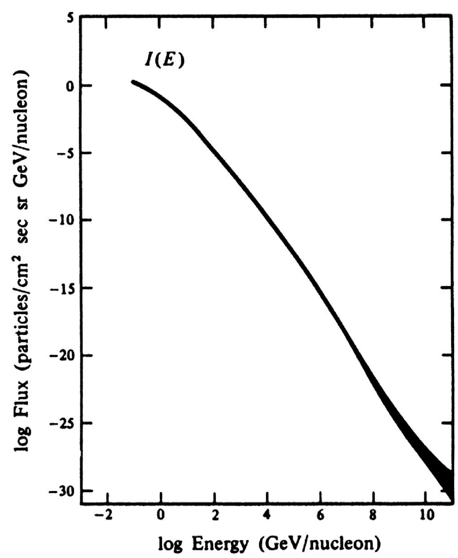

Figure 1: *Energy spectrum of the nuclear component of the primary cosmic rays.*

$$I(E) \propto E^{-2.6}$$

where $I(E)$ is the intensity (flux) of the nuclear component at energy E.

When a primary cosmic ray, e.g. a proton, enters the Earth's atmosphere it interacts with the nuclei of the atmosphere's atoms (mainly oxygen and nitrogen). From the interactions, new particles are produced (secondary cosmic rays), inducing in their turn new reactions with atoms of the atmosphere. This creates a hadronic shower. The word hadronic signifies that the produced particles are hadrons, i.e. strongly interacting particles, like protons, pions, kaons, etc. The word *shower* refers to the way the particle production develops in space (see Figure 2).

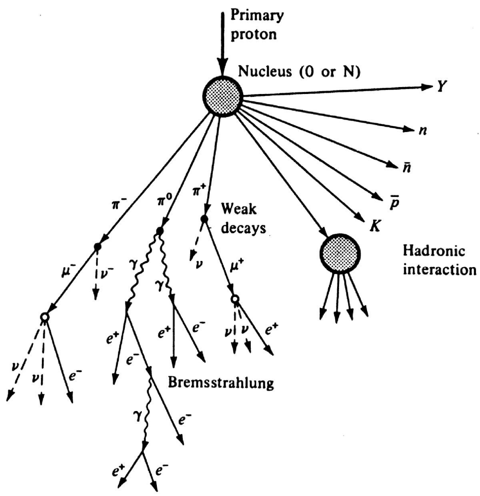

Figure 2: *A high-energy proton strikes an oxygen (O) or nitrogen (N) nucleus in the top of the atmosphere and produces a shower of particles.*

Antiparticles, like antiprotons, are also produced in this process. Unstable hadrons then decay weakly to electrons, muons and neutrinos. Photons are also produced, e.g. by π^0 decays or electron bremsstrahlung. Electromagnetic showers are created by electrons or by photons converting into electron-positron pairs, which emit new photons etc. Overall, a very high energy proton can produce a very extensive shower, covering many km^2 of the Earth's surface. By the time the showers reach the ground, they mainly consist of electron- and muon-neutrinos and muons. These are the cosmic muons that we observe in our experiment.

4 Muons and their decay

Muons decays as follows:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$$

Most of the muons decay in the atmosphere but some have high enough energies to reach our detector. Depending on their energy, they will either go through it or stop in the aluminium plate, which is located in the middle of the detector (Figure 4), where they will eventually decay.

5 What is the lifetime of a particle?

The lifetime of a particle is something that we define in the rest frame of the particle.We will take the muon as an example of a decaying particle but the following discussion is a general one and applies to all unstable particles.

If we take a muon and observe it in its rest frame, we can never tell in advance at exactly which moment the muon will decay, even if we know exactly when the muon was created. This means that the muon does not have a fixed time of life. The only thing that we can say is that at a specific moment in time, t, there is a probability, $P(t)$, for the muon to decay. We therefore say that the muon decay has a statistical nature.

Let us assume that, at time $t_0 = 0$, we have N_0 muons. Each one of them has the same probability to decay in a specific time interval. For example, in the interval $[t_0, t_0 + 10ns]$, each muon will have a probability P_1 to decay. It is convenient to define the decay probability per unit time, λ, which is a constant. We can now find the decay probability for any time interval dt: this will be equal to λdt, as we can check from the units of the variables λ and dt ([probability/time]x[time]). What does it mean that the decay probability in time dt is equal to λdt? It means that, if at time t we have $N(t)$ muons, at time $t + dt$, $N(t)\lambda dt$ muons will have decayed. This means that the number of muons has decreased by a quantity $dN = -N(t)\lambda dt$. The minus sign is there because $dN = N_{final} - N_{initial} < 0$. If we integrate this relation, we find the *exponential decay law*[6]

$$N(t) = N_0 e^{-\lambda t} \tag{1}$$

From quantum-mechanics, we know how to use the above relation in order to calculate the mean life of the muon:

$$\langle t \rangle = \frac{\int_{N_0}^{0} t dN}{\int_{N_0}^{0} dN} = \frac{\int_0^\infty t \frac{dN}{dt} dt}{\int_0^\infty \frac{dN}{dt} dt} = \frac{1}{N_0} \int_0^\infty t \lambda N dt = \frac{1}{N_0} \int_0^\infty N_0 e^{-\lambda t} \lambda t dt = \frac{1}{\lambda} \tag{2}$$

The variable $\langle t \rangle$ is also denoted by τ and is called the $lifetime$ of the muon. It is a constant because λ is a constant. We see that the lifetime of the muon is not a quantity that we can measure by detecting the decay of one muon only. We need to observe how an initial number of (many) muons decreases with time.

Let us now take Equation 1 and insert the lifetime of the muon, $\tau = 2.2\mu s$:

$$R(t) = \frac{N(t)}{N_0} = e^{-t/2.2} \tag{3}$$

where $R(t)$ is the ratio of the remaining muons at time t over the initial number of muons and t is measured in μs. We see this distribution in Figure 3.

In principle, the number of muons will never be zero, as the exponential never crosses the horizontal axis. In real life, what happens is that there should be (almost) no muons left after $20\mu s$ or so. If we take the derivative of Equation 3 we find the rate at which the ratio $R(t)$ decreases with time:

$$\frac{dR(t)}{dt} = e^{-t/2.2} \frac{-1}{2.2\mu s} \tag{4}$$

Then we find that, at $t = 0$, the rate is $1/(2.2\mu s)$. Suppose that this rate stayed constant with time. This would give us a linear decay law,

$$\tilde{R}(t) = \frac{\tilde{N}(t)}{N_0} = 1 - \frac{t}{2.2\mu s} \tag{5}$$

which is shown by the dashed line in Figure 3. Equation 5 tells us that if the number of muons that decayed per unit time was always equal to the value it had at $t = 0$, then at time $t = \tau$ there would be no muons left.

[6] This relation is also called the radioactive decay law for historical reasons because it was first found to describe the decay of radioactive nuclei.

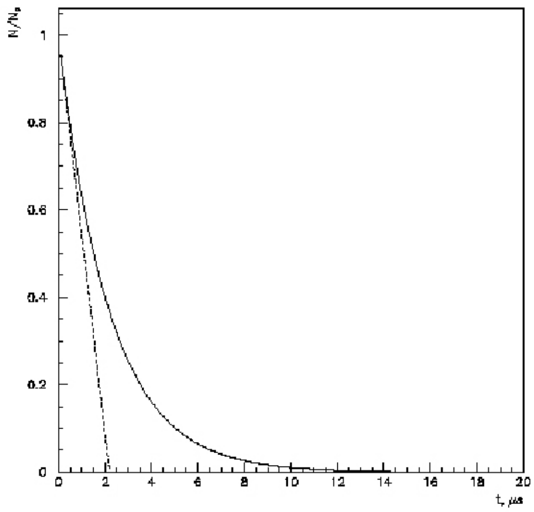

Figure 3: *Exponential decay law for muons (solid curve), see Eq.3. The dashed line shows the hypothetical linear decay law of Eq.5.*

6 The detector

Our detector is shown in Figure 4. Most of the muons pass right through the detector, however a fraction is stopped in the aluminium absorber, where they will decay. The muons come from above and will pass two scintillators (SC1 and SC2) before they stop. The positron from the decay can either be detected leaving the set-up upwards, as in the figure, or downwards. The magnet is not used in our experiment.

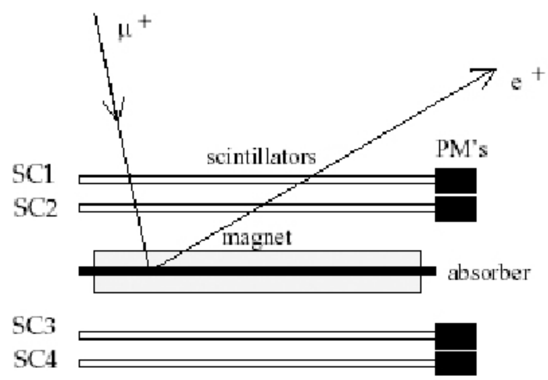

Figure 4: *The setup of the experiment (side view). The electronics is connected to the output of the photomultipliers (PM's).*

6.1 Scintillators

Scintillators are devices that detect the passage of charged particles. Our scintillators are made of plastic. When a charged particle passes through the scintillator it excites (gives energy to) the molecules of the scintillator. Soon afterwards the molecules emit light and return to their ground state. A single charged particle will typically cause around 20000 photons to be emitted per cm of traversed scintillator. The scintillators are so called because the light which is emitted from their molecules is a scintillation, i.e., a small flash of light. The emitted light is directed to the photomultiplier.

6.2 Photomultipliers

A photomultiplier is mounted after each scintillator and collects the light that was emitted by the molecules of the scintillator. The function of the photomultiplier is to convert the light to an electric pulse (analog signal). This is done as follows: the incoming light (photons) hit a photocathode (a piece of material at a negative electric potential). 10 to 30% of the photons cause the emission of an electron (photoelectric effect). The electrons are accelerated between a series of dynodes (pieces of metal at increasingly positive electric potentials). When an electron hits a dynode, 5 new electrons are emitted from the dynode. As the electrons traverse the dynodes, an avalanche of electrons is produced. Finally, all electrons are collected at the anode, where their initial number has been multiplied by a factor 10^6 or more. This is the pulse (analog signal) that we obtain from the photomultiplier. The photomultiplier is so called because it takes originally light (photo-) that converts to electrons which it multiplies (in the dynodes).

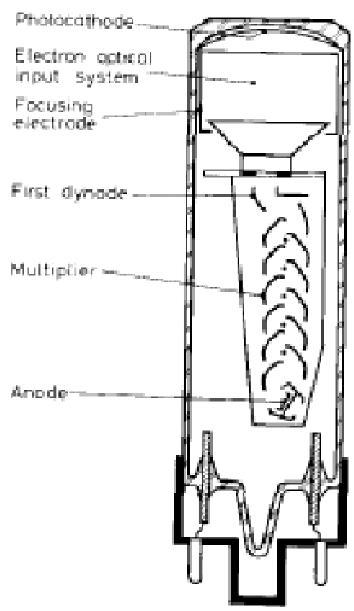

Figure 5: *A schematic view of a photomultiplier. Light comes in from above and emitted electrons are multiplied as they move downwards through the dynodes.*

The design of a photomultiplier can be seen in Figure 5. The outputs from the photomultipliers are connected to preamplifiers which give a signal strong enough to be detected by the logic.

6.3 Amplifiers

After the photomultipliers, there are amplifiers. The amplifiers take the signals from the photomultipliers and enlarge them (amplify them) so that they can be handled by the electronics. Both input and output signals are analog (i.e. proportional to the energy deposited by the particle that crossed the corresponding scintillator).

6.4 Discriminators

A discriminator is a device which converts analog to digital (0 or 1) signals as shown in Figure 6. When the signal A is given as input to the discriminator, the discriminator will produce a digital pulse C because the signal A exceeds the threshold of the discriminator. A low signal B which is smaller than the threshold, will be ignored and the discriminator will give a 0 pulse as output. The output of the discriminator is always a digital signal (square pulse).

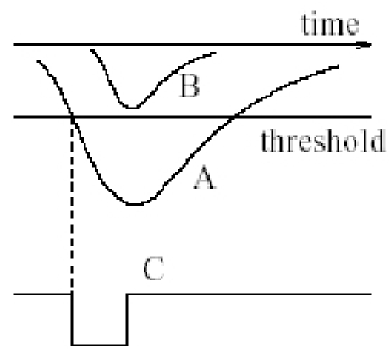

Figure 6: *Operation of a discriminator.*

6.5 Time-to-Pulse-Hight Converter, TPHC

The TPHC gives a square pulse output signal with an amplitude proportional to the time between a start and a stop signal.

6.6 Multi Channel Analyser, MCA

The MCA takes incoming pulses and stores them in different memory channels (bins) in such a way that the channel number is proportional to the amplitude of the pulse.

7 Setup

Figure 7 shows the electronics used in our setup. As start signal to the TPHC we use an incoming stopping muon *up AND NOT(down)* and as stop signal an electron emitted downwards *NOT(up) AND down.* The TPHC output amplitude will then be proportional to the decay time of the muon and these signals are sent to the MCA in the computer.

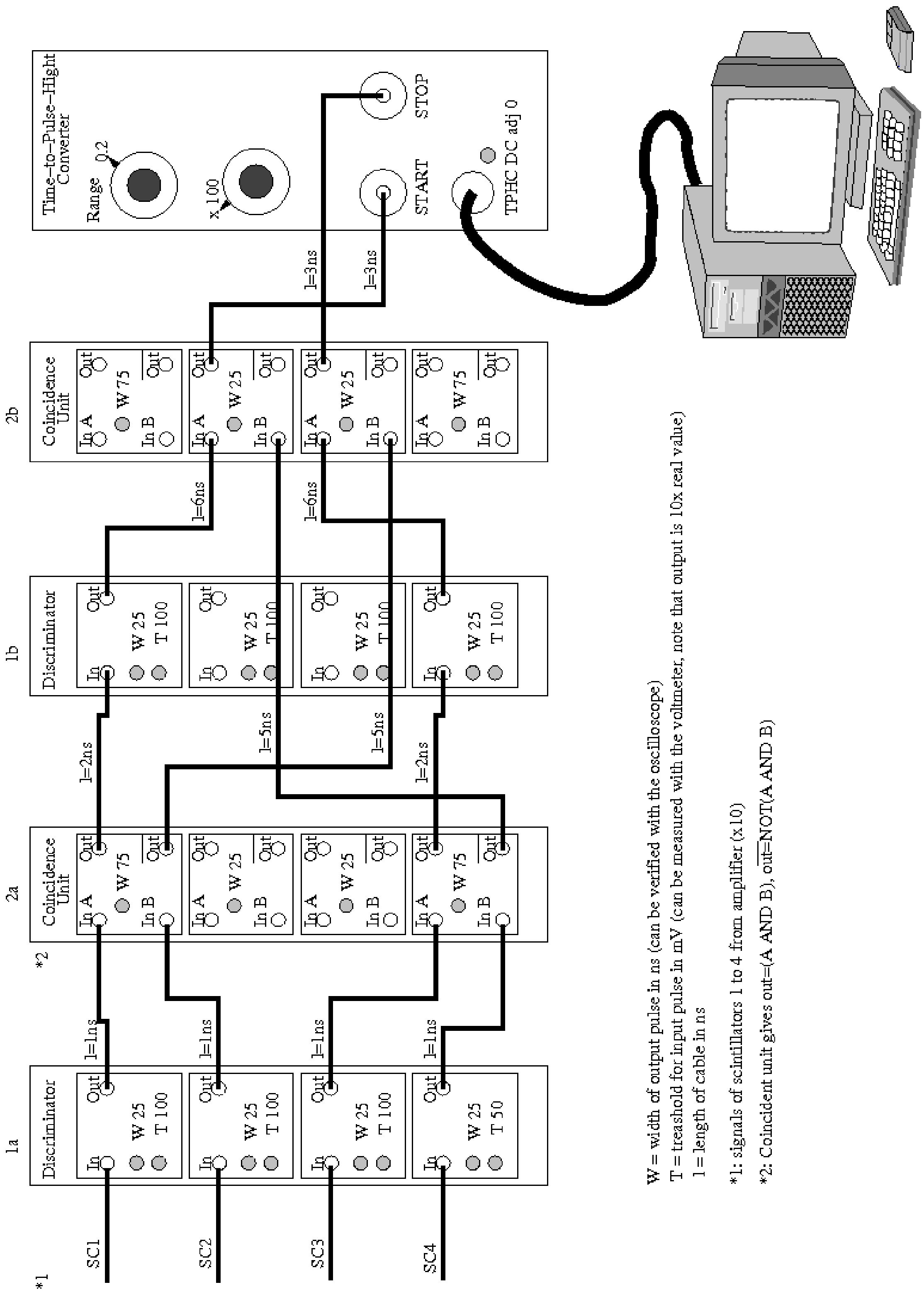

Figure 7: *Conceptual experimental setup of the electronics.*

A Units in High Energy Physics

The fundamental units in physics are of length, mass and time. In the familiar SI system, these are expressed as *meter* (m), *kilogram* (kg) and *second* (s). In high energy physics, these units are not very useful because the distances are much shorter than 1 m, the particles have masses much smaller than 1kg and the duration of processes is much smaller than 1s. Therefore, we need to introduce new units or modify the old ones.

- Length is usually expressed in *femtometers*. We write 1 fermi as 1fm and it corresponds to 10^{-15}m. The radius of a proton is about 1fm. The radius of a nucleus is a few fm.
- Time is usually measured in *nanoseconds or microseconds*. One nanosecond is $10^{-9}s$ and we write it as 1ns. One microsecond is $10^{-6}s$ or 1000 ns and it is written as $1\mu s$.
- The unit for energy is based on the so-called *electron-volt*, eV, which is defined as follows: an electron which is accelerated by a potential difference (voltage) of 1 Volt gains an amount of energy equal to 1 eV. As this is a very small amount, we usually multiply it by 10^6 to form 1 mega-electron-volt, MeV. If we multiply by 10^9 instead we obtain a giga-electron-volt, GeV. The mass of a particle is measured, for example, in MeV/c^2, where c is the velocity of light. This comes from Einstein s relation $E = mc^2$. As it is not convenient to divide by c^2 in the calculations, we use a unit-system where c=1 by definition. We also set $\hbar = 1$. This is called the system of natural units. For example, the mass of an electron is about 0.5 MeV and the mass of the proton is about 938 MeV. The particles momenta are also expressed in units of eV.

B AND, NAND and OR Gates

There are three kinds of gates that one usually use, AND gates, NAND gates and an OR gate but in our setup we only use AND and NAND gates. A gate is a device that takes as input two (or more) digital signals (0 s and 1 s) and combines them into one digital signal. The value of this signal depends on the kind of the gate. In Figure 8, we denote by A and B the input signals and by C, D and E the output signals of the gates. In Table 1, the values of C, D and E are given for all possible combinations of A and B.

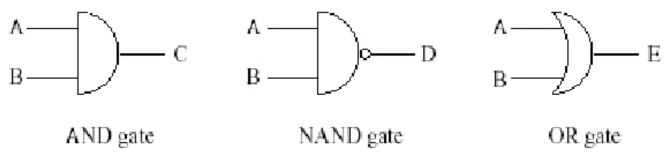

Figure 8: *The three kinds of gates that we use in our electronics: AND, NAND and OR.*

A (1st input)	B 2nd input	C (A AND B)	D (Not A AND B)	E (A OR B)
0	0	0	1	0
1	0	0	1	1
0	1	0	1	1
1	1	1	0	1

Table 1: *Input A, B and output C, D, E signals for the gates of Figure 8.*

From Table 1, we see that the output of the AND gate is 1 when both A AND B are 1. The output of the NAND gate is the opposite of the output of the AND gate (N in NAND stands for Not). The output of the OR gate is 1 when A OR B are 1. Therefore, the name of the gate denotes the operation of the gate.

C Report Tips

This sections contains a short list of guidelines that address some of the most common mistakes made by students writing lab reports. The attentive reader will notice that these rules are not necessarily followed in the rest of the lab manual. Please be a better writer than that and follow them in your report!

- Figures and tables must be numbered and have a descriptive text. The text should explain what the figure or table shows.
- Figures and tables must be referred to from the main text. For example, if you include a figure showing the experimental setup, you could refer to it by writing "The experimental setup is shown schematically in Figure 1."
- When writing the descriptive text for your figure or table, make sure it is in the correct location. Figure texts go directly *below* the figure. Table texts go directly *above* the table.
- When making plots, remember to label the axes. Units should be put in brackets. Writing "Time [s]" is correct. Simply writing "Seconds" is not.
- Avoid giving your plots "titles", e.g. by using the *title* command in MATLAB. This information goes in the figure text.
- Do not rely on colors to make your plots readable. They will be useless to color blind people or when printed in black and white. Lines can be solid, dashed, dotted and have varying thickness. Points can be represented by different symbols and be either hollow or filled. Writing "the dashed line" is fine, but writing "the red line" is not.
- Be consistent. Many words and phrases can be written in various different ways that are all acceptable but should not be mixed. For example, do not mix "aluminium" and "aluminum". Do not mix "the data is" and "the data are". Do not write "coincidence unit" in one place, "and-gate" in a second and "AND-gate" in a third. Pick a version and stick to it!
- Scalar variables should be typeset in italics. Vectors should be in boldface. Units should be plain text.
- A symbol should appear in the same way in equations and in running text. For example, distance d is given by

  $$d = |\mathbf{v}| \cdot t$$

  where $\mathbf{v}$ is velocity and t is time. Note that d and t are always in italics while $\mathbf{v}$ is always in boldface.
- Use a space between numbers and units. It's 5 kg, not 5kg.
- If in doubt, consult a style guide. A good one that contains many useful rules and recommendations is the guide used by the ATLAS experiment[1].

[1] https://cds.cern.ch/record/1110290/files/gen-pub-2008-001.pdf