MEASUREMENTS ON MUONS FROM COSMIC RAYS
Student experiment guide

Summary
This experiment is based on measurement of muons from cosmic rays. You will be introduced into some techniques from particle physics. Through measurements of the lifetime and the velocity of muons you will see the theory of special relativity at work!

At the end of this document you will find questions that will help you on your way during the experiment. You do not have to provide the answers to these questions in your report, but you may use them as a guide to your experiment.

Measurement of the lifetime and the velocity of muons
The purpose of the experiment is to explain why it is possible that muons reach the earth taking into account the measured values of their lifetime and velocity. Muons are produced at about 10 km altitude. It will turn out that on the average muons live approximately 2 microseconds. This means that they must travel by about 16 times the speed of light to reach the earth, which is, in view of special relativity, not possible. You're going to find the solution to this problem.

The lifetime measurement is based on the decay of a muon in two other particles, an electron and a antineutrino, it can be performed with one detector. When the muon hits the detector a scintillation is produced. Most of the muons fly straight through the detector, but a small fraction is captured. The trapped muons decay after a while, and the electron originating from the decay process produces a second signal.

The velocity measurement is based on a method that is called 'time of flight measurement ". In particle physics, this type of measurement is often used in experiments with particle accelerators. In our experiment, the velocity measurement is performed with two detectors, about 2 meters apart. From the measured time differences of muons passing through both detectors the velocity can be determined.

The interpretation of the measurements is complicated by the fact that our data do not represent directly the lifetime and the velocity of the muons, but that we measure distributions. Keeping in mind the statistical character of the decay and taking into account detector effects it turns out to be possible to determine the values of lifetime and velocity from these distributions.

Cosmic rays
What is cosmic radiation and how are the muons which we will measure, produced?

The discovery
Around 1909 it was known for some time that plate electroscopes discharged faster than would be expected. The air in the electroscopes became electrically charged regardless of the degree of insulation. The first idea was that this was caused by radiation from radioactive substances in the earth. Theodore Wulf , however, discovered that an electroscope at the top of the Eiffel Tower (300 m) discharged more quickly than on the ground, what did not agree with the hypothesis that the phenomenon was caused by radiation from the earth. Victor Hess examined how far radiation out of the ground could reach and he concluded that such radiation could not have enough effect at an altitude of 300m. In 1910, Victor Hess started to develop an electroscope that could survive the harsh conditions of a hot air balloon and would

maintain good insulation under these conditions. In 1912, Victor Hess took this electroscope along in a balloon and discovered that as he rose the electroscope discharged faster. At a few kilometers altitude the effect was so strong that Hess could no longer avoid the possibility of radiation from space. Hess also saw that his measurements remained the same during a solar eclipse on April 12, 1912. From this he concluded then that the Sun could not be the main source of the radiation. In 1936 he was awarded the Nobel Prize for his work. Since its discovery and up to now many measurements have been made on cosmic rays. New experiments are still being built.

Where are we now?

From space a lot of phenomena come to us, electromagnetic radiation (light, microwaves, gamma rays), neutral and charged particles and perhaps a lot of things more that we do not know. The charged particles that come to us consist for 89% out of protons, 10% out of helium nuclei and a remaining 1% distributed among all the other particles of the periodic system. Only charged particles are considered to be cosmic rays. The origin of these particles is not always known. Charged particles can be deflected in their path to the earth by interstellar and galactic magnetic fields. Once arrived on earth, their direction does not give information about the direction where they come from. In our solar system streams of charged particles coming from the sun cause a magnetic field that deflects cosmic particles. The result is that at high solar activity, the intensity of the cosmic rays that arrive on the earth, is smaller. Deflection is also caused by the magnetic field of the earth.

Supernova remnants like the Crab Nebula can be a source of cosmic rays. One can infer this from the synchrotron radiation that is emitted by remnants of a supernova by electrons that move in spirals in the magnetic field of the supernova remnant. This synchrotron radiation has an energy between 10 and 1000 keV.

The measured intensity (the flux) of cosmic rays as a function of their energy is given in Figure 1. The dependence of the intensity of the cosmic rays of their energy is given by the following formula:

$$I(E) = 1.8E^{-2.7}$$

I (E) is the number of particles with energy E in GeV per m^2, per second and per steradian. The formula is purely empirical and is obtained from a best 'fit' to the data points in figure 1. The highest energy value of cosmic rays that has been measured is around10^{20} eV. This is equivalent to 16 Joule. If a ball of 100 g would have a speed of 64 km/h it would have this energy. Cosmic rays coming from our galaxy typically have energies between 100 MeV and 10 GeV.

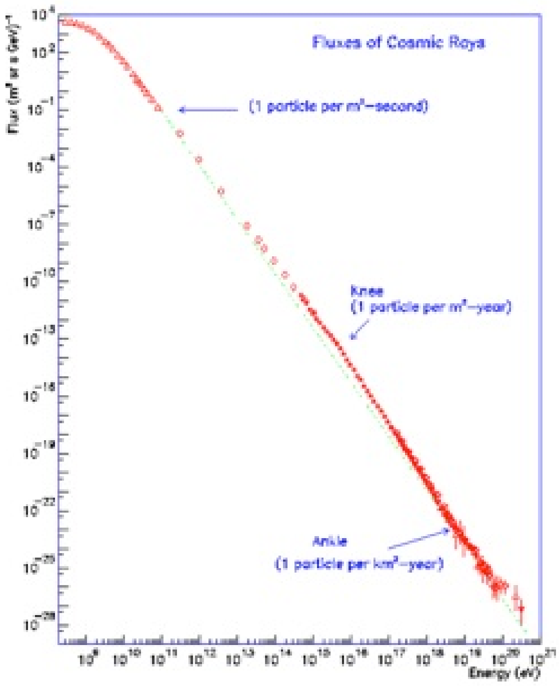


Fig. 1 Energy spectrum of cosmic rays

What do we see from it?
If primary cosmic rays enter the atmosphere of the earth, the charged cosmic particles can collide with a nucleus of an atom in the atmosphere. Before the cosmic rays reach the earth they have already undergone one or more interactions with the nuclei of air molecules. Depending on the energy many or little pions will hereby be produced. These secondary pions also can expire interactions thereby sometimes decaying to a muon. In each collision, the particles lose energy and, ultimately, most of them are stopped in the atmosphere thereby producing electrons and photons. The particles that arrive on earth are mainly muons and secondary electrons and photons. Depending on what happens and what is the primary energy, there will be a more or less larger shower of particles. These showers can sometimes be very large but the larger they are the less is their probability: a shower with a width of 10 km^2 is expected about once in a year.

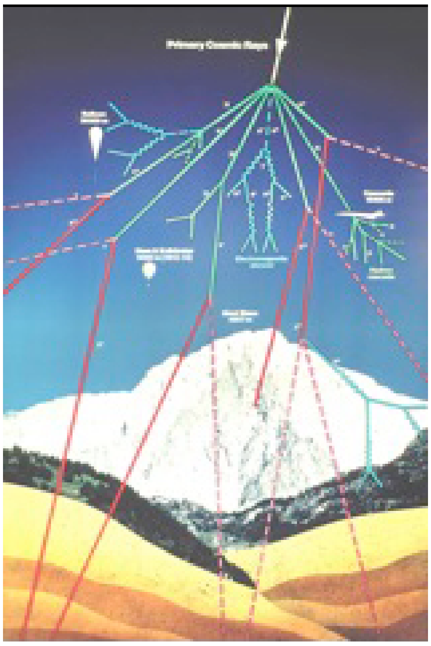
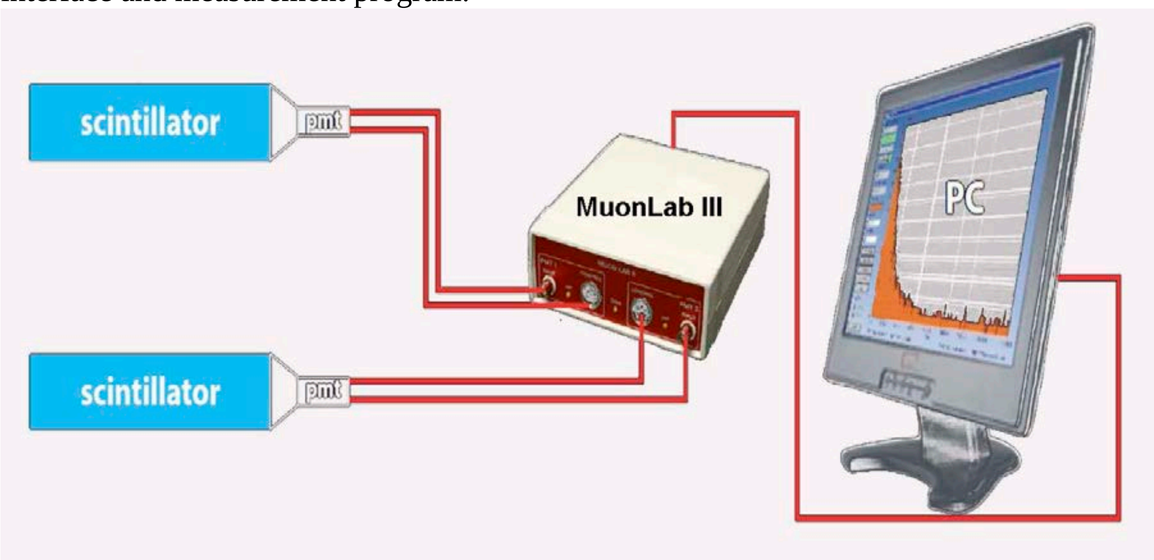


Fig. 2

The experimental arrangement
The experimental arrangement is shown schematically below. The detectors consist of scintillator material and are connected to a photomultiplier tube (PMT). As a muon passes the detector a light pulse is produced, which is detected by the photomultiplier. The PMT converts the light pulse into an electric pulse. The resulting electric signals are read out by means of an interface box MuonLab III and stored in the computer by using a LabView interface and measurement program.



Observing charged particles
As a charged particle passes through matter, it will lose energy in small portions by electromagnetic interactions with atoms and molecules which can be excited or ionized. The interaction process depends on the type of material, type of particle, energy and charge of the particle. Typically along the route of the charged particle through the material many molecules will be excited. There are optically transparent materials in which a small part of the excited molecules will emit the absorbed energy in the form of a visible photon. This kind of materials are called scintillation materials. Some organic materials exhibit the behavior

that, when excited to a higher level by the passage of a charged particle, a flash of light occurs when a molecule emits a photon in falling back to the ground state. This type of organic materials usually have a benzene ring in their molecules, such as polystyrene or polyvinyl toluene. In the experiment that we have prepared, the muons will be observed with two long and thick pieces of solid material, consisting of a transparent plastic doped with a few percent of an organic scintillator material.

The photomultiplier tube

A photomultiplier tube converts a light signal into an electrical current. The tube consists of a cathode, a number of dynodes, and an anode.

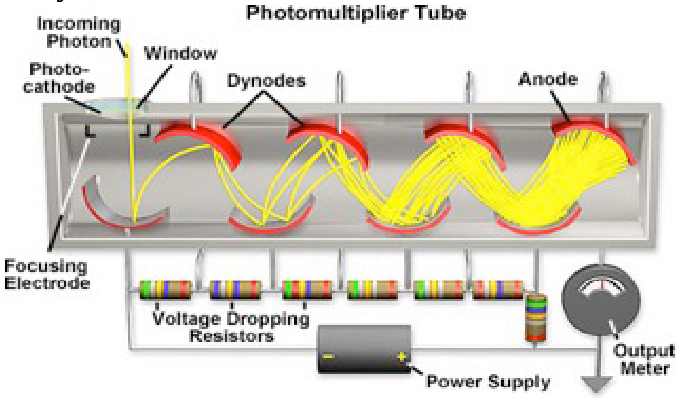


Fig. 3 Principle of a photomultiplier

When a photon strikes the cathode, it can release an electron in the light-sensitive material which covers the cathode by the photo-electric effect. Light-sensitive materials to be used at the cathode should have a low work function for electrons and a high efficiency, which means that there should be electrons in the outer orbit like in Na or K. Ordinary metals such as copper also have a low work function, but they have a low efficiency and are therefore not suitable to serve as a photocathode.
If we would drop the released electron directly on the anode, the current produced would be too small. Therefore, there are between the cathode and the anode a number of electrodes which will multiply the number of electrons. These electrodes, called dynodes, have a potential difference with respect to each other and with respect to the cathode so that the electrons step by step are accelerated . They are provided with a layer of material that emits at least two electrons when an electron falls on. With 10 dynodes the gain of the tube in that case is at least 2^{10}. In a resistor connected to the anode we see a current of 2^{10} electrons. In practice, the voltages on the dynodes are provided by a voltage divider between a high voltage and earth potential. Depending on the type of voltage divider, the gain of the PMT will have a value between 10^6 and 10^8. The cathode can be on earth potential and the anode to a positive high voltage or the cathode can be at a negative high voltage and the anode on the earth. Both systems have their advantages and disadvantages.

Fig.4 example of a photomultiplier tube

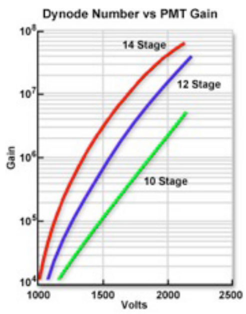


Fig. 5 gain of a photomultiplier tube

An important property of the photomultiplier tube is the time resolution, that is the time that elapses between the arrival of a photon and the delivery of the anode pulse.
This time depends on the different paths of the electrons through the tube in moving from the dynodes to the anode. If we want to measure times with scintillation counters, we would like to have this distribution as small as possible. This could result in a special geometric design and a shielding against the earth's magnetic field of the interior of the tube by surrounding it by a cylinder of mu-metal.
Even in a completely darkened room we still measure an electrical pulse. This we call that the dark current of the photomultiplier tube. It is caused by the release of electrons from the cathode via thermal emission.

3. References
Useful links may be found on the webpage of the HiSPARC project: http://www.hisparc.nl. The HiSPARC project is a project in which high school students build scintillation detectors and provide measurements of ‘muon showers' in the atmosphere.
On http://www.interactions.org you may find information about the world of Particle Physics and Astroparticle Physics.

THE MUONPARADOX

Questions and instructions as a guide for your measurements.
1. A muon decays after some time in other particles. The average lifetime of a muon is about $2x10^{-6}$ s. Muons see a chance to get on earth from a great height. Which 'Newtonian' velocity would you expect for these muons?
2. How can you measure the lifetime of muons? Enter the relevant formula (s).
3. Does the run time of the photon in the scintillator play a role in the measurement of lifetime?
4. Draw a schematic arrangement for a velocity measurement, in which you are going to use scintillation material and one or more photomultiplier tubes for detecting a muon passing through your detector.
5. Which information do you need to do a velocity measurement. And how accurate would your observation minimally (order of magnitude) have to be in order that you can measure the expected velocity of the muons.
6. The muons that come into your detector can come from all sides. Explain that you cannot directly measure the velocity, but only a distribution. Can you make a prediction on the distribution of velocities? With distribution we mean: a histogram with on the horizontal axis, the velocity in intervals and on the vertical axis how often a given velocity occurs. Which means that
if you always exactly would measure the same velocity, then the histogram would show a sharp peak for the corresponding interval.
if all possible velocities would occur arbitrarily, each interval in the histogram would show the same height
7. What would you expect for the angular distribution of the muons: will there be as many muons per time unit in the vertical direction as almost horizontally
8. When the pulse have reached the end of the photomultiplier tube, we usually have to transport the pulses through cables to the readout interface. How fast do you expect a pulse propagating in a copper wire?
9. Consider which effects would have influence on the measurement of the time at which a muon passes your detector.
10.There are many muons per unit of time coming into your detector, sometimes simultaneously. Consider the probability that two successive muons could be interpreted as a muon decay. Also consider this effect for the velocity measurement.
11.The amount of radiation measured increases as you progress from the earth's surface, but decreases at very high altitude. What could be the explanation for this.
12.How fast (in terms of the speed of light c) do muons have to fly to reach the earth after they are made at 10 km altitude considering their average lifetime of 2 microseconds? Is this a problem?

Setup of the experiment
Use the figure elsewhere in this document as a guide for the setup. In addition to the following instructions use your common sense!

Detectors
Connect the supplied cables, two for each detector. The cable for the voltage supply to the PMT has a six-pole DIN plug and the cable for the signal is a standard coaxial cable with BNC connector.

PC software / hardware
The MuonLabIII signal analyzer is connected to the PC via an USB cable. The software is installed on the C-disk of the computer.

MuonLabIII interface
Open the program and click on the white arrow top left. Explore the tabs, see manual.

Adjustments
It takes some experience to find the right settings. Be aware that the higher you set the high voltage for the PMT's, the more noise you get. However, if you set the HV too low, the detector is not efficient. To the threshold this applies in the reverse way.
As starting values choose a high voltage of about 1500V. The default value for the threshold in the MuonLab III program is 150 mV.
How many muons per second do you expect?
Look at the pulse shape (only with channel 1).

The measurements

Velocity measurement:
You will need two detectors. First, put these detectors together and choose Start in the Delta Time tab. If all is well you see a Gaussian distribution (normal distribution). This is your zero measurement. As a first impression estimate the average value of the time difference. For a detailed analysis you can edit the data in text file with Excel.
Place the detectors in a crossed position and determine the velocity of the scintillation light in the detector. Save the results
Place the detectors as far apart as possible. Keep the sides at which the signals are measured above each other even if you have different length detectors
Collect data (at least 100) and work it out. Understand what you have measured. Otherwise, ask the supervisor.

Muon velocity
Explain qualitatively the shape of the distribution with a focus on the start, the middle and the end point values
What is the typical time difference; what is the typical velocity of your muons? A detailed analysis can be done using Excel.
What is the Lorentz factor

Lifetime measurement:
In principle you only need one detector, however, the MuonLab interface measures two detectors simultaneously.
|Choose Start in the Life Time tab
After 10 minutes you will have only about 10 measurements, but you can see if the experiment works.
After an hour you can decide whether everything is properly set. Note the setting, cables, detector, HR and threshold etc.
Let the lifetime measurement go for many hours

Muon lifetime:.
The distribution you will measure has a long tail. Where does this come from and how can you correct for this?
Explain the observed distribution and calculate the mean lifetime of the muon

Which minimal value is needed for the Lorentz factor or gamma factor in order that muons can reach the earth?
Why is the measured Lorentz factor smaller

Appendix I
Processing data in Excel.
If you want to do this properly you need to invest some time in making and analyzing histograms in Excel

Appendix II
What is the probability of a primary interaction?
We assume that the flux of cosmic particles (number of particles per second through an area of 1 cm^2) is given by F. The density of particles in the atmosphere is given by ρ (g/cm^3).
Then, of course, the probability that per second an interaction takes place in a length L (cm), is proportional to F, ρ and L in accordance with:

$$N_{\text{int}} = FL\rho\frac{N_A}{A}\sigma(pA \to X)$$

where N_A is Avogadro's number, and A is the atomic weight of the nuclei of the atmosphere. The proportionality constant σ(pA → X) is called the collision cross-section, or cross section of the interaction, in which a proton of within an atom collides to a random final state X. The cross-section has the dimension of surface. The cross-section of a proton-proton interaction is approximately independent of the energy of the incoming particle and has the value $\sigma = 5 \cdot 10^{-26}$ cm^2. The proton-neutron cross-section is the same as the proton-proton cross section. If we consider a nucleus as a sphere filled with protons and neutrons, the cross section of proton-nucleus interaction will be $\sigma_{pA} = A^{2/3}\sigma_{pp}$.
The interactions that take place in L per second, will decrease the flux. We write this as

$$\frac{dF}{dL} = F(L)\rho\frac{N_A}{A}\sigma(pA \to X)$$

This differential equation has the solution

$$F(L) = F(0)e^{-L/L_{\text{int}}}$$

in which the interaction length $L_{\text{int}} = 1/(\rho\frac{N_A}{A}\sigma_{pA})$. If we assume that the atmosphere consists of N_2 and is an ideal gas is of 1 atmosphere, then: $N_A\rho/A = 2.7 \cdot 10^{19}$ cm^{-3} together with $\sigma_{pA} = A^{2/3}\sigma_{pp} = 2.8 \cdot 10^{-25}$ cm^2 leads to $L_{\text{int}} = 1.27$ km. So 60% of the incoming particles will interact in the first 1.2 km from our atmosphere.