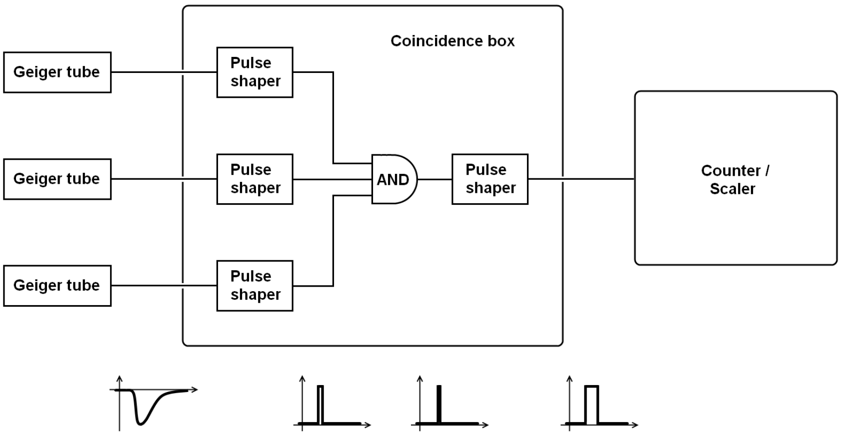
Number 138970-EN	*Topic* Particle physics, cosmic rays				
Version 2017-10-03 / HS	*Type* Project / long-running measurement	*Suggested for* grade 12+		*p.* 1/4	

Objective
Demonstrating the particle cascade from cosmic rays; demonstrating a penetrating component of the radiation

Principle
Three Geiger tubes connect to a coincidence box. By successive addition of steel plates in front of the three Geiger tubes you first observe an increase in the coincidence counts, levelling off to a constant value.

The experiment repeats some of Bruno B. Rossi's historic discoveries of the behaviour of cosmic rays. Rossi invented in 1930 the first electronic coincidence circuit. Today, complicated coincidence measurements are indispensable in particle physics research.

Equipment
Myon observatory
Geiger tube, large area (Qty. 3)
Coincidence box
Geiger counter
(Possibly datalogging equipment)



The coincidence box
The signal from each of the three Geiger tubes pass a circuit that shortens the pulse width to 1 µs.

The three signals are then joined in an AND gate and only if all three are active *simultaneously*, the output of the AND gate is activated.

The pulses from the AND gate output are given a suitable width (45 µs) before exiting the box.

Setting up and checking equipment

Place the setup where it can be left undisturbed for the time measurements are performed.

Fix the rail in a vertical position. Place a single steel plate temporarily in the absorber magazine. Position the holder with the Geiger tubes to leave 6-7 cm between the tubes and the absorber plate.

With the Geiger tubes in a triangle like this, it is impossible for a single particle to penetrate all three tubes.

Connect each tube to an input on the coincidence box.

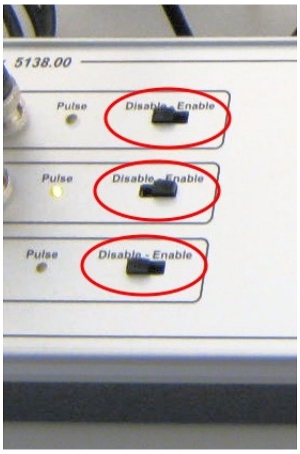
The coincidence count rate is very low, so we must check the setup carefully before measurements begin:

Connect the output from the coincidence box to a Geiger counter – this is the simplest way to do the initial check (even if datalogging is used later). Set the counter to count continuously and start it.

On the coincidence box: Set all three slide switches at *Disable* initially.
Setting **one** switch at a time at *Enable*, check that the background radiation that makes the LED flash now and then is also registered by the counter.

After that, possible datalogging equipment can be connected. We recommend the free program *Datalyse* (download English version from dtalyse.dk) which works well with Geiger counters 513600 or 513610.

In order to be totally sure you can repeat the check of one of the individual inputs.



Checking input 2

Procedure

Place all three switches in the *Enable* position.

Remove the absorber plate.

Zero the counter. Start the measurement. Wait approx. 24 hours.

Write down the absorber thickness (initially 0 mm), the counting period and the count.

Measure the thickness of one absorber plate and place it in the magazine.

Start a new 24 hour measurement.

The result will surprisingly be larger than without the absorber.

Continue increasing the absorber thickness with 0ne plate per measurement.

When an absorber thickness of a few centimetres is reached, the counts have peaked and will drop slowly. Now you can add 2 or 3 plates at a time (gradually even more at a time.

Continue, until you run out of absorber plates. (Additional plates can be purchased!)

Data processing

As you know, the uncertainty on the raw count *N* is given by $\Delta N = \sqrt{N}$.

Calling the counting period *T*, the counts can be converted to count rates with the expression

$$r = \frac{N}{T}$$

… with the associated uncertainty

$$\Delta r = \frac{\Delta N}{T} = \frac{\sqrt{N}}{T}$$

Plot the count rates as a function of absorber thickness.

Draw the uncertainties of the count rates as vertical line segments above and below each data point. This makes it easier to visually assess how to draw a soft curve to describe the behaviour of the count rates, based on the complete set of data.

Interpretation

The following page sketches a bit of our current knowledge of the particles involved – which, however, was not known at the time when B.B. Rossi performed the experiment.

In brief, the result is that when penetrating matter, relativistic electrons and photons will create a cascade of particles distributing the energy until the energy per particle becomes too low to pair production. From that point, the particles are rapidly decelerated.

In principle, muons behave the same way, but the length scale is increased approx. a factor of 40,000 compared to electrons.

Explain how the experimental curve can be explained, based on two different components in the radiation.

If we assume that part of the radiation we register is electrons – how much energy do they carry? (Approx.)

Facts on electrons and photons

The energy of a relativistic electron decreases exponentially when passing through matter.

After penetrating the thickness x the energy is

$$E_x = E_0 \cdot \mathrm{e}^{-\frac{x}{L_\mathrm{R}}}$$

Where L_R is called the radiation length and is given by

$$\frac{1}{L_\mathrm{R}} = 4\left(\frac{h}{2\pi mc}\right)^2 Z(Z+1)\alpha^3 n_\mathrm{a} \ln\left(\frac{183}{Z^{\frac{1}{3}}}\right)$$

Here, m is the electron mass, Z is the atomic number, n_a is the density (atoms per volume) and α is the *fine structure constant* (1/137).

In this energy range, energy is primarily lost through emission of photons (bremsstrahlung).

High-energetic photons are primarily absorbed through pair production and their number decreases exponentially according to

$$I_x = I_0 \cdot \mathrm{e}^{-\frac{x}{\lambda}}$$

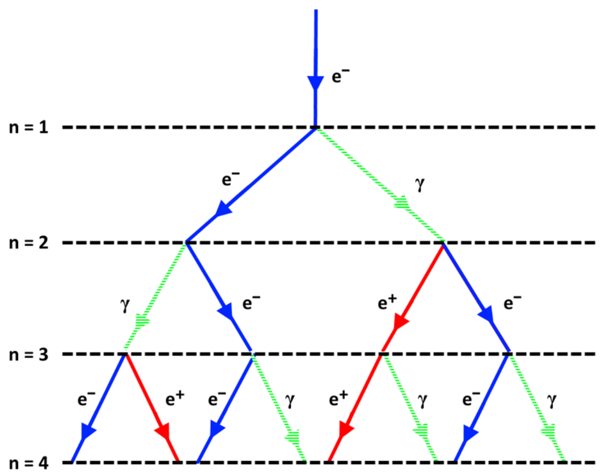
Where λ is the mean free path length for photons, given by

$$\lambda = \frac{9}{7} L_\mathrm{R}$$

We notice that the characteristic lengths are of almost the same size.

A simplified model of the cascade can now be formulated:

For each radiation length, the number of particles doubles. (Electron → photon + scattered electron; photon → electron + positron.) The energy is assumed distributed equally among the particles.



The cascade evolves as long as the energy is higher than E_C, the critical energy above which pair production dominates over ionization.

Below this point, the cascade abruptly stops developing and the remaining energy is lost through collision processes.

The number n_max of "generations" in the cascade can be found as

$$n_\mathrm{max} = \frac{ln\left(\frac{E_0}{E_\mathrm{C}}\right)}{\ln(2)}$$

As a rough estimate, we have

$$E_\mathrm{C} = \frac{800\ \mathrm{MeV}}{Z + 1{,}2}$$

If cosmic radiation consists of mono-energetic electrons, the number of particles in the cascade will grow exponentially until some maximum absorber thickness is reached, after which it will decrease to zero

Facts on muons

Muons exist as both positively and negatively charged particles (μ^+, μ^-). A muon is approx. 200 times heavier than an electron. Muons are unstable with a half-life of 2.197 µs.

Muons behave like electrons, but caused by the mass difference, the radiation length for muons is approx. 200^2 = 40,000 times larger than for electrons.

Muons from the cosmic radiation that reaches the sea level has an average energy of approx. 4 GeV.

The energy loss by ionisation of muons is relatively constant 2 MeV per g/cm^2. The thickness of the atmosphere is approx. 1000 g/cm^2, meaning that muons must be produced with an average energy of approx. 6 GeV.

Literature

Peter Dunne: *Demonstrating cosmic ray induced electromagnetic cascades*. The article can be found here:

http://hst-archive.web.cern.ch/archiv/HST2000/teaching/expt/muons/cascades.htm

Bruno B. Rossi's work is described in a Wikipedia article:

http://en.wikipedia.org/wiki/Bruno_Rossi

Teacher's notes

Concepts used

Pair production
Bremsstrahlung

Radiation length
Critical energy for pair production

Mathematical skills

Graph plotting with uncertainties
Evaluation of complex formula
Exponentially decreasing functions

About the equipment

The Geiger tubes specified can be substituted by 3 pcs. of 513565 Geiger sensor, large area, Jack – as long as the two types are not mixed.

The specified Geiger counter along with the associated communication cable can be substituted by a similar counter or datalogging equipment. The coincidence box is provided with a cable that also fits for instance Pasco's digital adapter.

You may consider to add a cheap UPS to the setup in order to avoid mains drop-outs to affect the measurements.

Random coincidences

In coincidence measurements, *random coincidences* appear as a kind of "background radiation" that you normally need to account for. The count rate for random coincidences is given by

$$r_\mathrm{R} = K \cdot r_\mathrm{A} \cdot r_\mathrm{B} \cdot r_\mathrm{C} \cdot \tau^2$$

Where r_A, r_B and r_C are the count rates for the three inputs, τ is the pulse width (10^{-6} s), and K is a constant in the order of magnitude 1 (that depends on experimental details).

With count rates for the individual inputs in the order of 0.5 s^{-1}, a random coincidence will happen once every 10^5 years.

Detailed equipment list

Specifically for the experiment

514200	Myon observatory
513800	Coincidence box

Standard lab equipment

512525	Geiger tube, large area (Qty. 3)
513610	Geiger counter (or older model 513600)
512565	USB communication adapter for 513600