PROBLEM N°10
PARTICLE DETECTOR FOR DUMMIES

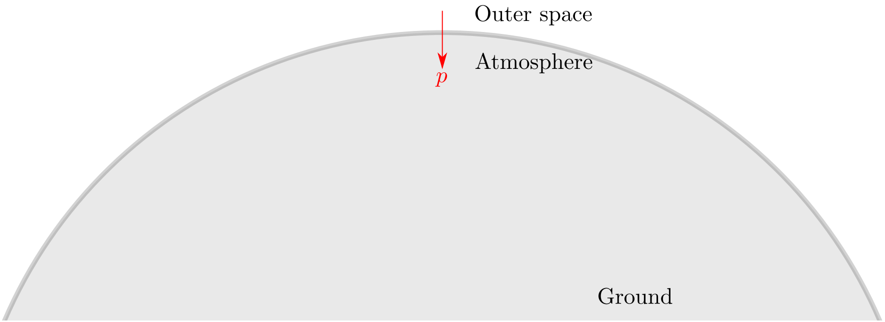
Team Ecole polytechnique

The problem

*Build a simple device that can **detect cosmic ray particles**.*
*Characterize the **particle identification** capabilities of your device.*
*Try to test your device in **different conditions** and also try to obtain the **energy spectrum of the cosmic ray particles**.*

What are cosmic rays?

Primary cosmic rays : 90 % protons, 9 % alpha particles, 1 % others



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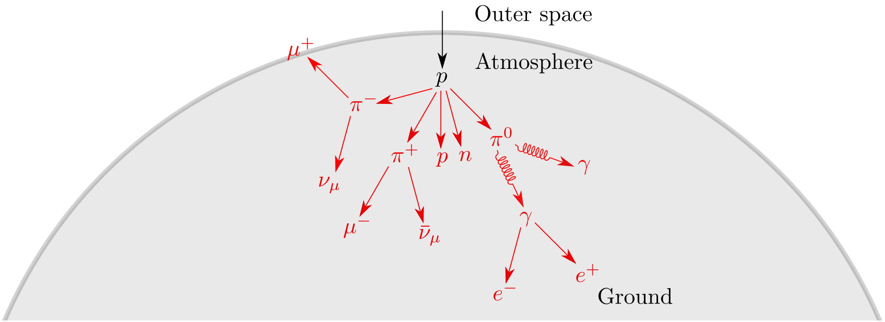


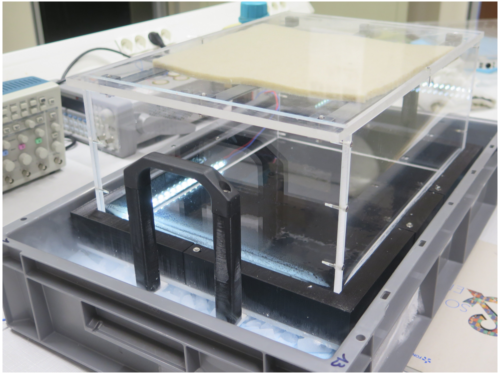
Secondary cosmic rays : 75 % muons

Muons of 4 *GeV* have a Lorentz coefficient $\gamma \simeq 40$, allowing them to reach ground before decaying thanks to special relativity.

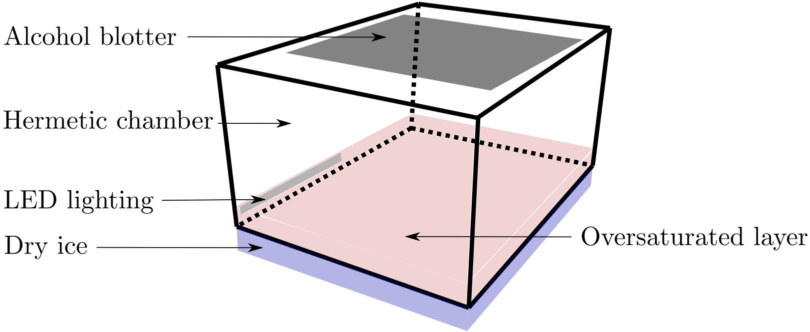
What are cosmic rays ?

	Fermions			Bosons
Quarks	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
Leptons	e electron	μ muon	τ tau	Z Z boson
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
	1st generation	**2nd generation**	**3rd generation**	H Higgs boson

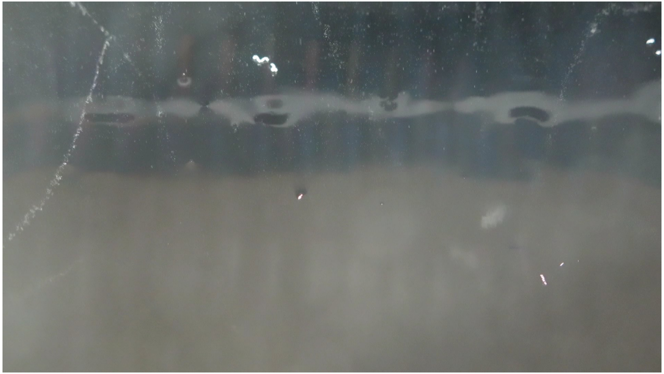
First device : a cloud chamber



How does it works



Observations



Particle identification capabilities

Observable particles : $e^-, e^+, \mu^-, \mu^+, p^+, He^{2+}, K, \Lambda, \Xi, ...$

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For some charged particles with energies between 1 and 100 MeV, the energy loss is given by Bethe formula :

$$\frac{dE}{dx} = -\frac{4\pi}{m_e c^2}\frac{nq^2}{\beta^2}\left(\frac{1}{4\pi\varepsilon_0}\right)^2\left[\ln\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)}-\beta^2\right)\right]$$

With : m_e the mass of electrons, c the speed of light, n the electron density of the material, q the charge of the particle, ε_0 the vacuum permittivity, β the boost of the particle and I the mean extraction potential of the material.

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Alpha particle and delta ray

Low energy electron

Muon or high energy electron

Gamma ray ?

Pair production : $\gamma + n \longrightarrow e^{+} + e^{-} + n$

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We could get the momentum p of the particle, then from :

$$E = \sqrt{(pc)^2 + (mc^2)^2}$$

With E the energy of the particle, c the speed of light and m the mass of the particle

We could get it's energy E.

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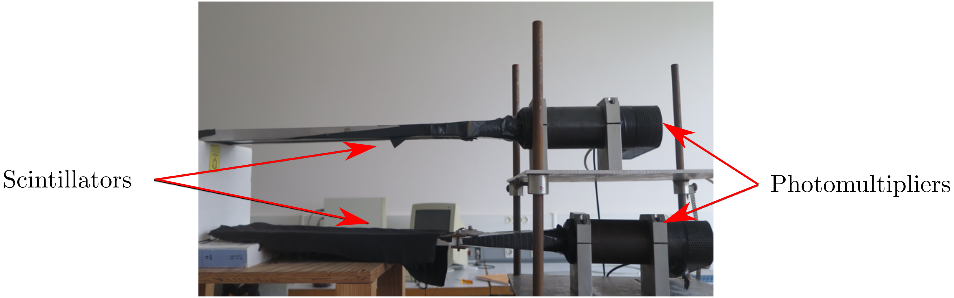
But :

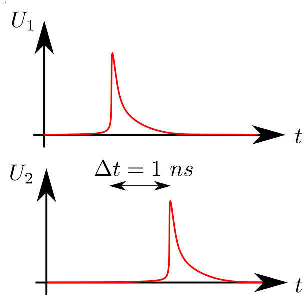
- To deflect a 1 MeV muon with a radius of 10 cm, we would need a uniform field of 4 T on the surface of the chamber
- We need to assume the charge and mass of the particle to get it's energy

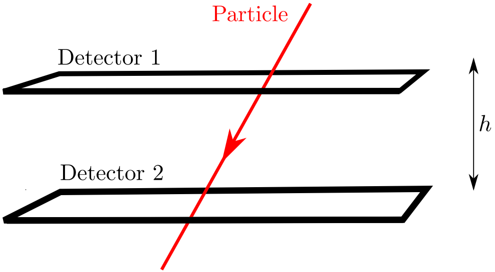
Second device : scintillation detector



[1.]C.Lagoute ; BUP, **Réalisation d'un détecteur de muons : une approche de physique du XXème siècle au lycée**, 2009

Coincidence detection





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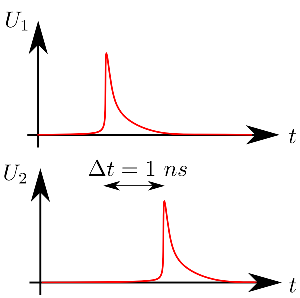

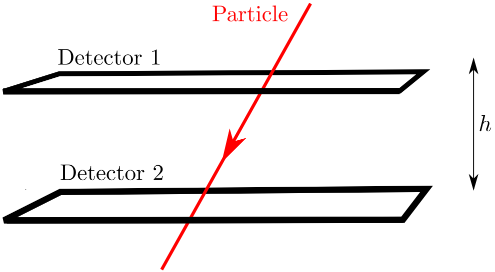

We detect particles going downward with at least 2 % the speed of light

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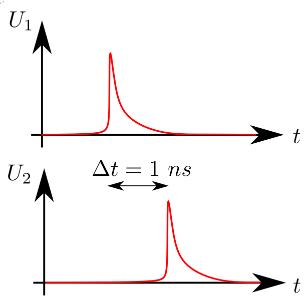
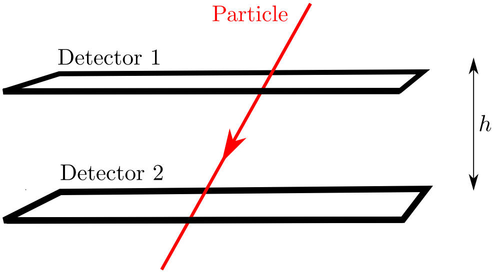
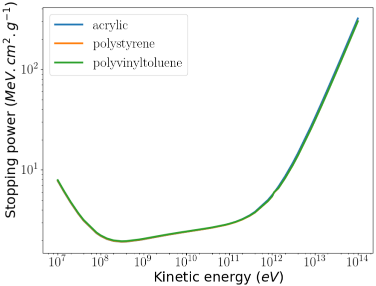




We detect particles going downward with at least 2 % the speed of light and we can get the energy spectrum of those particles

Theory of energy deposition in matter

Mean energy deposition depends on total energy [4] :



Muon stopping power

[4.]Groom, Mokhov, Striganov ; A.D.N.D.T **Muon stopping power and range tables** 10 MeV – 100 TeV, 2001

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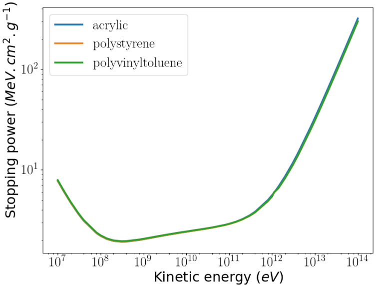

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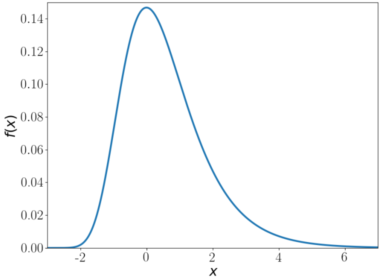

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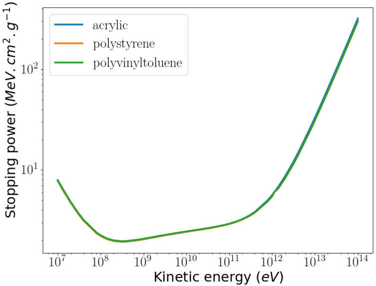

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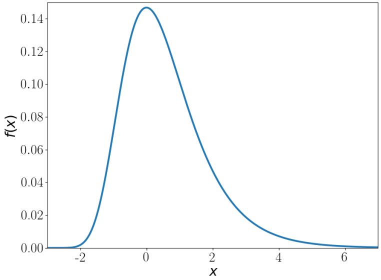

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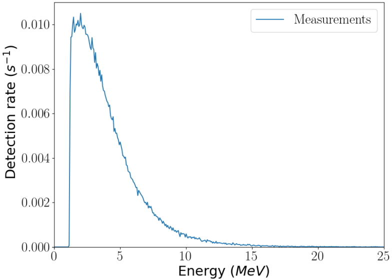
Energy spectrum

With three days of measurement and 150964 detections

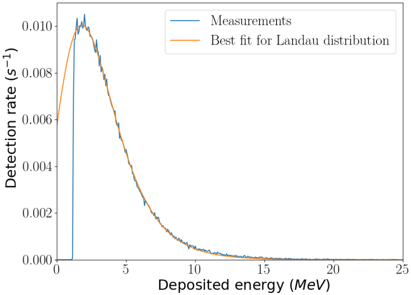


Our energy spectrum

The cut for low energies is due to a threshold reducing electronic noise.

Interpretation of our spectrum

The spectrum we measure is only the Landau distribution :



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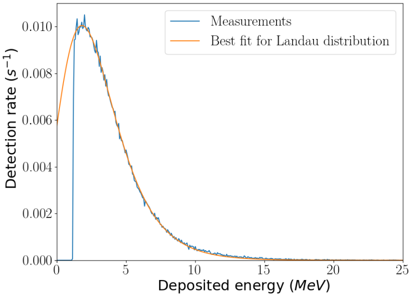

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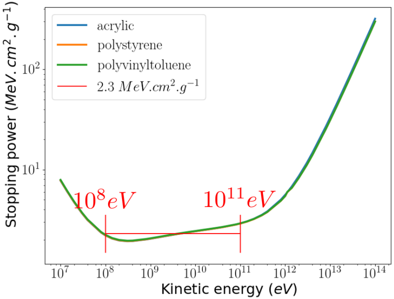
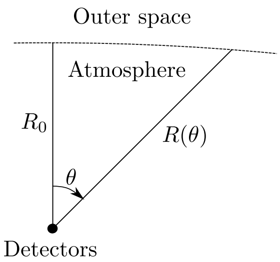
The stopping power is the same for all the particles :



Muon stopping power [4]

Muon flux anisotropy

Model : grazing incidence rays take more time to reach the surface and have more chance to decay.



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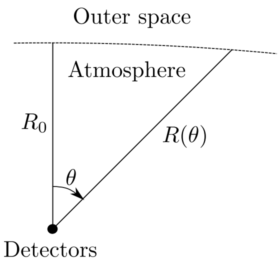

Hypothesis

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- E_0 : energy of muons

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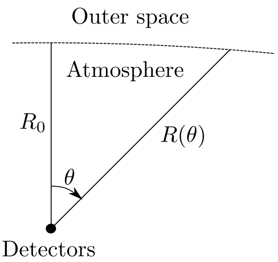

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We have :

- $R(\theta) = \frac{R_0}{\cos(\theta)}$
- $P(t_{decay} > t) = P_0 \exp(-\frac{t}{\gamma \tau_0})$

With γ the Lorentz coefficient and τ_0 the proper lifetime of muons

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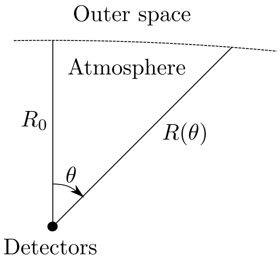

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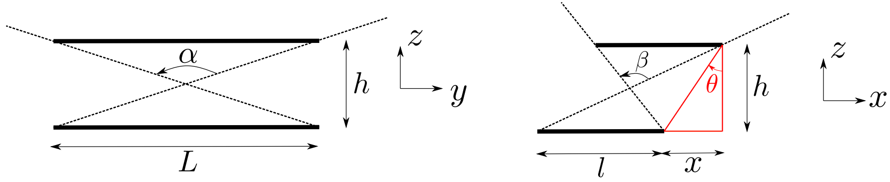
We get the flux of muons $\phi_{th}(\theta)$ as :

$$\phi_{th}(\theta) = \phi_0 \exp\left(\frac{-\lambda}{\cos(\theta)}\right), \text{ where : } \lambda = \frac{m_\mu c R_0}{E_0 \tau_0} \text{ and } \phi_0 \text{ is a parameter}$$

Measuring the flux anisotropy

We simply slide the one detector relative to the other :



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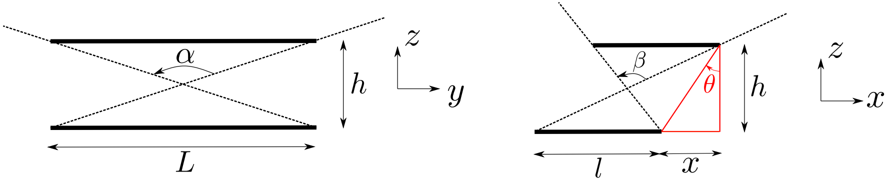

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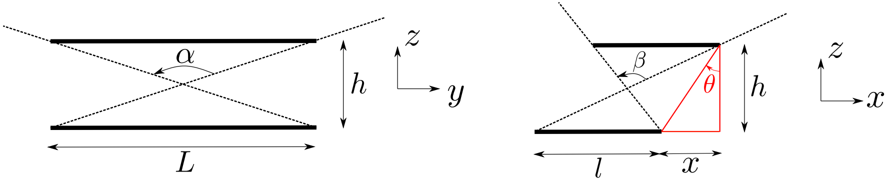

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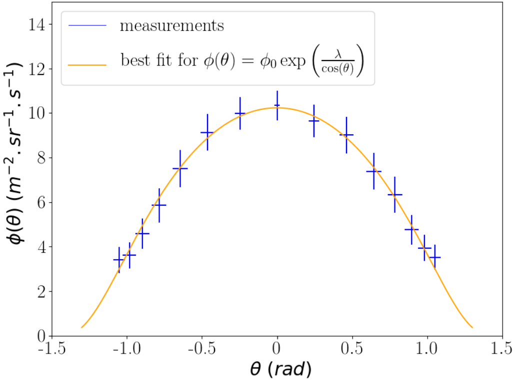
We then get from the number of detection to the flux with time and geometric normalization.

Result of the measurement



Muon flux anisotropy

Another measurement of muon's energy

We had :

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- $m_\mu = 2.10^{-28}\ kg$ the mass of muons
- $c = 3.10^8\ m.s^{-1}$ the speed of light
- $R_0 = 10 - 100\ km$ atmosphere's thickness
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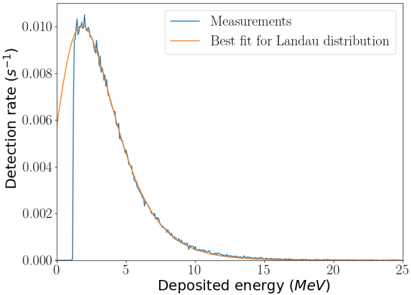
[5.]G.Remmen, E.McCreary ; Journal of Undergraduate Research in Physics , **Measurement of the speed and energy distribution of cosmic ray muons**, 2012

It is coherent with our spectrum

The spectrum we measure is only the Landau distribution :



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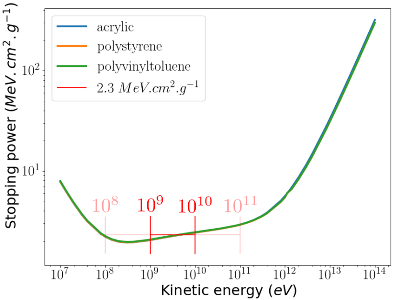
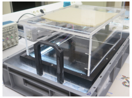
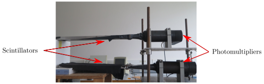


Muon stopping power [4]

Conclusion

Build a simple device that can **detect cosmic ray particles**





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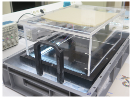
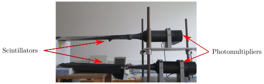
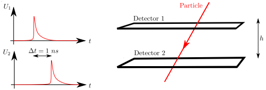




Characterize the particle **identification capabilities** of your device



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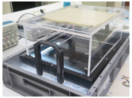

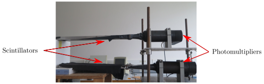

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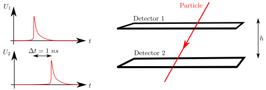
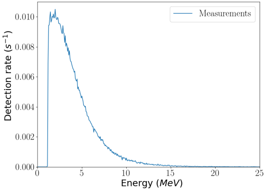
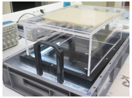


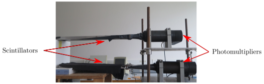
Try to obtain the **energy spectrum** of the cosmic ray particles



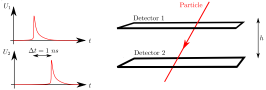
Conclusion

Build a simple device that can **detect cosmic ray particles**



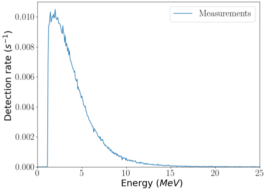


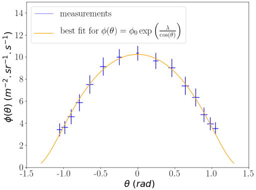
Characterize the particle **identification capabilities** of your device



Try to obtain the **energy spectrum** of the cosmic ray particles

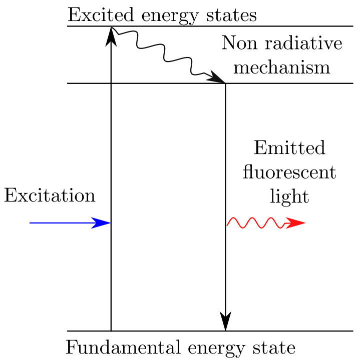
Try to test your device in **different conditions**



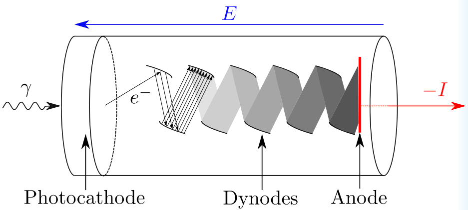


Scintillator and photomultiplier

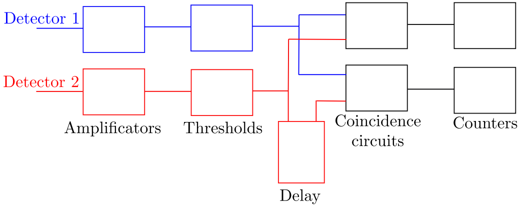
Scintillator : fluorescent plastic plate, producing photons from excitations

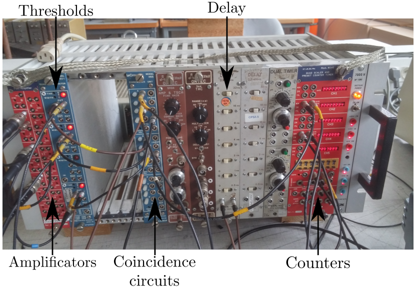


Photomultiplier : association of a photocathode and dynodes, producing a measurable current from single photons.



Coincidence detection



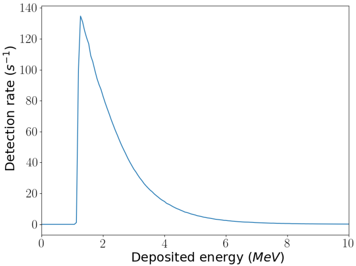


Principe of electronic processing

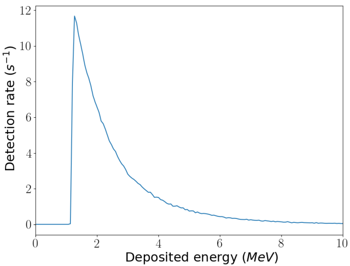
We detect particles going downward with at least 2 % the speed of light

Energy calibration of the detector

Tentative with radioactive sources :



Cesium 137

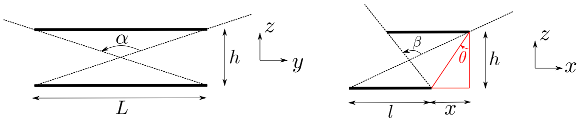


Sodium 22

The expected value of the muon spectrum is the stopping power of the detector [2] :

$$2.3\ MeV.g.cm^{-1} \times 1\ g.cm^{-1} \times 1\ cm = 2.3\ MeV$$

Geometric normalization of the flux



With basic geometry :

$$\alpha = 2\arctan\left(\frac{L}{h}\right), \beta = \arctan\left(\frac{l+x}{h}\right) + \arctan\left(\frac{l-x}{h}\right)$$

Then, the solid angle from the center of the detector is :

$$\Omega(L,l) = 4\arcsin\left(\sin\left(\frac{\alpha(L)}{2}\right)\sin\left(\frac{\beta(l)}{2}\right)\right)$$

We then have to take the solid angle from any point in the detector, it gives the following integral for $C(\theta)$:

$$C(\theta) = 4\int_{u=0}^{L}\int_{v=0}^{l}\Omega(u,v)dudv$$

The normalization follows, considering we are detecting the flux from only one direction at a time :

$$\phi_{measured}(\theta) = \frac{N_{detections}(\theta)}{TC(\theta)}$$

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