Cosmic Radiation

Theoretical Physics and Detection Project

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Introduction

During the year of 2018 – 2019, I decided to write my 'Travail Personnel' about cosmic radiation. I have been working on this subject at the *Entreprise LEM.SCIENCE Astronomie* since the end of 2017. However, I did a big amount of work additionally to my obligatory tasks.

Due to the fact that my 'Projet Personnel' is astrophysics, this work provided me with a great opportunity to gain knowledge and even do some real research in this sector. That is why I decided to do further theoretical research in that sector as my 'Travail personnel'.

This 'Travail Personnel' has two goals:

- Deepen my knowledge about particle physics to better understand the constituents of cosmic radiation and the processes they undergo.
- Present the practical work and the studies I realised as part of the ‚Astronomie'. This includes data processing software and an own weather station.

Therefore, I will firstly describe the basics of the ‚Standard Model', the current dominating theory of particle physics, including some further explanations concerning cosmic rays. Then, I will treat the primary cosmic rays, following up with the secondary particles and their creation as their multiple interactions with the atmosphere. Finally, I will describe our detector at the ‚Astronomie', the two practical projects I realised by myself, and very shortly list the studies I realised at the ‚Astronomie'. Attached is code I wrote for my projects and some scientific articles, which either I wrote or are based on my software.

Cosmic Radiation - Theory

Introduction to Particle Physics

Particle Physics is the part of physics which tries to explain the most fundamental levels of matter and radiation. The most dominant theory of today is the so-called 'Standard Model' and was started to be developed during the second part of the 20th century. With the Standard Model, we can explain 3 of the 4 fundamental forces: Weak interaction, Strong interaction and Electromagnetism. The fourth fundamental force, gravity, is explained by the theory of relativity and until now, no connection between these parts of physics was proven. In this part, I will explain the basics of particle physics.

Terms

Electrical charge

An electrical charge is the charge that causes matter to be affected from electromagnetic fields. This simple principle applies: Two positive charges or two negative charges push each other apart. Two opposite charges attract each other. Neutral charges aren't affected.

In particle physics, the charge of particles is expressed as a multiple of the elementary charge, the charge of an electron, the smallest charge existing: $1{,}602\,176\,6208 * 10^{-19}\,C$ (Coulomb). The most common symbol for the elementary charge is *e*.

When referring to the electrical charge of a particle, we commonly use $Q(x)$, where x is the symbol of the particle.

Spin

The spin of a particle is the angular momentum of the corresponding particle. We can think of it as the rotation of the particle itself. However, this is physically not true. When creating magnetic fields, we can back-solve the size and charge of it and find out the angular momentum of the electrons creating this field. If this angular momentum were the speed of rotation, the speed would exceed the speed of light, which simply is not possible.

Therefore, the spin or angular momentum of a particle is just a property it has like mass or charge, but without really spinning. Nevertheless, this spin is necessary for many different reasons in particle physics.

In particle physics, the spin is usually expressed as a multiple of the reduced Planck constant: $\hbar = 1.054571800 * 10^{-34}\, J * s$. The Planck constant itself is a proportionality constant for the relation between frequency and energy of a quantum particle, like a photon or an electron. The reduced Planck constant is simply the normal Planck constant divided by 2π. This facilitates working with angular frequencies. Angular frequencies describe the angular displacement per unit of time and are preferred to classic frequencies (Hz) in modern physics.

Antiparticle

In particle physics, every particle has an antiparticle. The difference between a particle and his antiparticle is only their physical charge, which means that their electrical charge is opposite as is their colour charge. This colour charge is described in quantum chromodynamics and is responsible for the strong interaction, but in this Travail personnel, I will not go in depth in this branch of physics.

As notation, we usually put a line over the symbol of a particle to indicate that it is an anti-particle. The symbol of the anti-particle of an up-quark, or also anti-up-quark would be: $\bar{u}$.

Energy

In particle physics, one of the most important properties is energy. Energy needs to be transferred in order to observe any kind of movement, hence heat too. At absolute zero (0 K / -273,5°C) for example, when there is absolutely no heat at all, there is no energy and nothing is moving, not even on a subatomic level. Energy is conclusively responsible for movement and heat.

Every particle has an energy too. In this case, we can say, that this property dictates how much influence a particle can have on its surroundings and often indicates how it interacts with other particles.

Here an example to understand the energy of particles: Our interaction is between a car, which represents the particle we are interested in, which crashes against a concrete wall, any other particle or composition of particles. The property which represents energy in this example is the durability and mass of the car. For our first interaction, we take a little car, like a Smart, and let it crash against a wall. Intuitively we know, that the wall remains relatively unaffected and the Smart is smashed to pieces. The same applies for low-energy particles. The other participant of the interactions doesn't change much, but the particle itself is practically blown to hell and mostly decays. Now we repeat the same experiment, but with a Jeep. The wall will sustain some damage as will the Jeep. This time, our particle had more energy, which is why the other one is more affected. Now imagine what happens when a military-grade tank crashes against that wall. The tank sustains minimal damage and the wall will be shattered. This example neglects of course a great number of factors. Furthermore, this example does not work by for every situation in particle physics. Nevertheless, it should give a pretty good idea of what energy of a particle is.

The SI unit for energy is Joule (J). One joule corresponds for example to the energy needed to move a body over a distance of 1 metre with a force of 1 Newton. In particle physics the unit electronvolt (eV) is most commonly used, very often with prefixes (kilo, mega, giga…). One electronvolt approximately corresponds to $1{,}6 * 10^{-19}\,J$.

Energy-mass equivalence

In particle physics, mass and energy describe the same property due to the famous relation Albert Einstein found: $E = mc^2$. It says that the mass of a particle multiplied by the speed of light squared equals its energy. Therefore, in particle physics, mass is very often expressed in the unit $\frac{eV}{c^2}$, because $E = mc^2 \Leftrightarrow m = \frac{E}{c^2}$.

Mean lifetime

Due to the weak interaction, almost every particle decays at some point. In particle physics, we express the average time of how long a particle exists before decay as mean lifetime.

Half-life

For decaying particles, in physics, there is something called half-life. A half-life says how many particles have decayed after specific times. After one half-life, there is only half of the particles left. After two half-lives, only a fourth of the initial number of particles is left. A muon for example has at rest a half-life of 1,56 µs. That means if there are a million muons, after three times the half-life (1,56 µs * 3), only 125000 muons would be left (1'000'000/8). We can calculate the fraction remaining with $\frac{1}{2^n}$, where n is the number of half-lives elapsed.

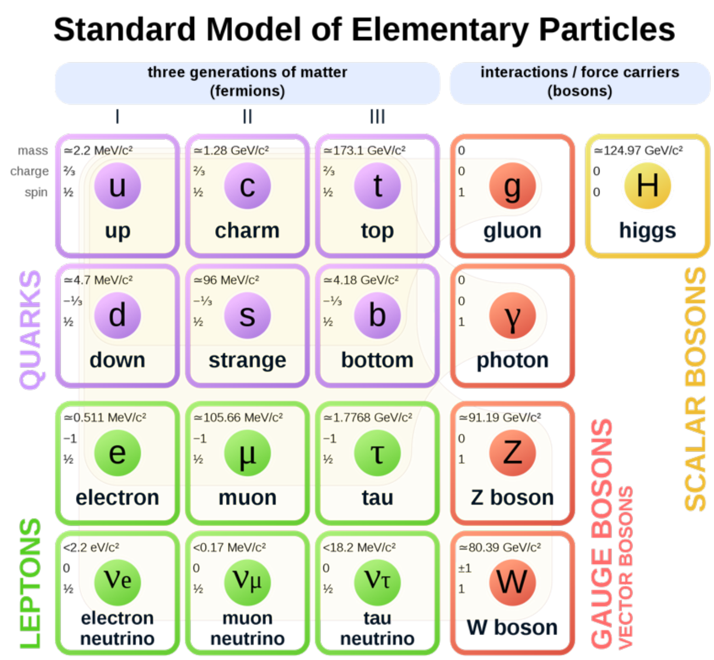
Half-lives elapsed	Fraction remaining
1	1/2
2	1/4
3	1/8
4	1/16
n	$1/2^n$

Heisenberg Uncertainty Principle

The Heisenberg Uncertainty Principle is the basis of all quantum physics. It describes the fact that we can never be really certain what the true nature of a particle is:
To observe anything, we need light, which is an electromagnetic radiation carried by photons. At low energies, photons cannot be reflected from elementary particles, because the photons' wavelengths are simply too big. Low energy photons thus just pass over the particles. If we were to try to observe the particles with higher energy photons, the photons would interact with the particles. This interaction changes the true nature of the particle we want to observe. Therefore, we can never be certain what a particle really looks like. We can only observe small blurs of influence the particle has on its surroundings.
That is why the physicists came up with a mathematical principle called point particles. They describe the particles as points to mathematically apply their influence.
Furthermore, those blurs of particles don't have to have a clearly defined position but can be probability clouds. The best and most common example are the electron orbitals. In an atom, an electron doesn't have a defined orbit around the nucleus, but it is described as where the electron probably is.
The important part of this principle is that these particles that I will describe are not really small spheres flying around, but blurs of influence which are described mathematically as particles to simplify calculations.

Elementary particles

In particle physics, we distinguish between elementary particles and composite particles. On this table, every elementary particle of the Standard Model is listed. Some tables differ from each other. For example, on some tables, the two rows of the leptons are switched. Nevertheless, the table shows, except some details like this, always the same. It is divided into two main categories: Fermions and Bosons.



Fermion

Every particle (composite particles too) which has a half-integer spin is defined as a fermion. On the table of the Standard Model, the fermions comprehend the first three columns, which are again subdivided into groups vertically and horizontally.

Three generations of matter

Vertically, they are subordinated by their generation of matter. There are three generations of matter. Between these generations, there is only one difference: the mass / energy. This property gets higher with the generation. The more energy a particle has, the less stable it is. This means, it will decay much earlier into lower generations. Therefore, in our current universe, we almost only find particles of the first generation. In some rare cases, we can find particles of the second generation. The third generation of matter is even rarer and has close to zero influence on our universe.

Horizontally, the Fermions are subordinated into Quarks and Leptons.

Quarks

Quarks are a fundamental constituent of matter. There are six quarks in total. The most common quarks, those of the first generation of matter, are the Up-Quark and the Down-Quark. The up-quarks have a charge of 2/3 of an elementary charge and the down-quarks have a charge of – 1/3 *e*. The charm (second generation) and top (third generation) have the same properties as the up-quark except for their much higher mass. The strange and bottom are the more energetic particles of the down-quark.
Nevertheless, quarks are never found alone. We can only find them within the different composite particles. That is why it is possible that they have less than an elemental charge as electrical charge. In composite particles, their charges add up to multiples of the elementary charge. Quarks make up every Hadron, either in pairs of two or three. As every other particle, quarks too have an antiparticle.
Furthermore, they are the only particles in particle physics which interact with every fundamental force.
The term for the classification of quarks is flavour. For example, the up-quark has the flavour up and the charm-quark has the flavour charm.

Leptons

The Leptons are besides the Quarks the other group of the elementary fermions. In the table, they occupy the 2 last rows of the fermions.
The first row of the leptons consists of the electron and its heavier generations. Their electrical charge is -1*e*. The heavier generations are called Muon and Tau. The antiparticle of an electron is called ‘positron’.
The particles in the second row of the leptons are the three generation of neutrinos. The first generation is called electron neutrino, the second-generation muon neutrino and the third-generation tau neutrino. Neutrinos all have a neutral charge. That is one of the reasons that they only interact per weak interaction. Finally, they are also the particles with the least energy of the fermions.

The baryons, which are made up of quarks of three, are fermions too.

Boson

Every particle (composite particles too) which has an integer spin is defined as a boson. On the table of the Standard Model, the bosons are found in the last two columns. There are two groups of bosons, which comprehend elementary particles, gauge bosons and scalar bosons, and two more, which are all composite particles.

Gauge Bosons

The particles in the fourth column of the table of the Elementary particles are all gauge bosons. Their defining property is that all the gauge bosons have a spin of 1. A gauge boson is a particle is a particle which carries one of the fundamental forces. In the current table of the standard model, we find four gauge bosons:

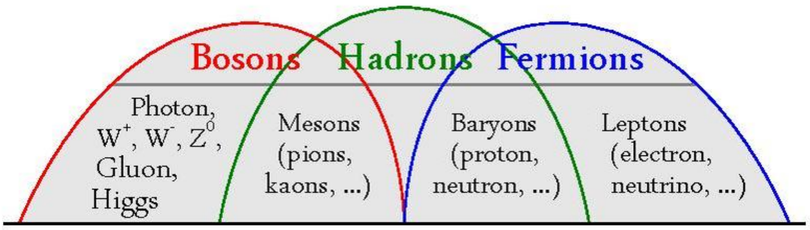
- Photon
  The photon is a particle which carries the electromagnetic force. For example, optical light can be described as made up of photons due to the fact that light is a small part of the electromagnetic spectrum. Theoretically, it has absolutely no mass, but is pure energy, because no mass can travel at the speed of light.
  The property defining the influence electromagnetic force has on particles is the electric charge.
- Gluon
  The gluon is the particle responsible for the strong interaction, which is, as the name predicts, by far the strongest fundamental force. Essentially, the gluons are responsible for holding quarks together to form hadrons and furthermore, they bind protons and neutrons to create atomic nuclei.
  The property of a particle which defines how it interacts with the strong force is their colour charge.
- Z^0 and $W^\pm$
  The two last gauge bosons in the table of the Standard Model are the Z boson and the W bosons. These particles actually comprehend three different types of particles: The Z^0 boson, which is neutrally charged, the W^+ boson, which has a charge of +1*e*, and finally the W^- boson which has a charge of -1*e*. These three bosons carry the weak interaction, which is responsible for radioactive decay. This weak interaction is hence responsible for the decay of cosmic rays.

Scalar boson

By definition, a scalar boson has a spin of 0. There is only one fundamental particle which fits that description, the Higgs Boson. In the table of the Standard Model, we find it in the upper right. The existence of this particle was only proved on 14 March 2013. This particle has very complex implications. Essentially however, through the whole universe, there is a field of these particles. When particles move through space, they interact with the Higgs field. Due to this interaction, the Higgs field drags on the particles and makes them experience perturbations. Only this allows electrons for example to even experience time and therefore have the property of mass. The two massless particles on the table of the Standard Table the gluon and the photon, do not interact with the Higgs field. Therefore, those particles do not have mass and do not experience time. Why they don’t interact with the Higgs field is still an open question in particle physics.

Composite particles

In particle physics, the most part of the particles are combinations of these elementary particles. These composite particles are also called Hadrons. They are always made up of quarks. There are two different types of Hadrons:



Baryons

This group of Hadrons is made up of three quarks and are composite fermions. Therefore, they always have a half-integer spin. They always combine in a way that their electrical charge is always integer. The two most common baryons are in almost every atomic nucleus, the proton and the neutron. They are the most essential part of almost all of the matter in our universe. We therefore call the matter made up of atoms baryonic matter.

Due to the quarks, baryons are subject to the strong interaction. They also interact with the weak interaction, gravity, and, if electrically charged, electromagnetism.

As already mentioned, baryons always contain three quarks. These are called triquarks. Some physicists argue that there could be baryons made up of more than three quarks, but always in odd numbers: pentaquarks (five quarks), heptaquarks (seven quarks), nonaquarks (nine quarks) etc. In theory, they could exist, but their existence is far from generally accepted.

Here are the two examples of the neutron and the proton:

Proton

A proton is made up of two up-quarks and one down-quark. This composition is notated: uud

The common symbol for this baryon is p^+. The charge of a proton is the sum of the electrical charge of these three particles:

$$Q(p^+) = 2 * Q(u) + Q(d) = +\frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e = +\frac{3}{3}e = +1e$$

A proton therefore is positively charged of $1e$.

Furthermore, the proton is the only baryon which never decays, when it is in a vacuum. Every other baryon decays sometime.

Neutron

A neutron is made up of one up-quark and two down-quarks (udd). The common symbol for this baryon is n^0. The charge of a neutron is as follows:

$$Q(n^0) = Q(u) + 2 * Q(d) = +\frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e = 0$$

A neutron has conclusively a neutral electrical charge.

Even though a neutron is stable in an atomic nucleus, in a vacuum it decays. It has a mean lifetime of about 15 minutes.

These are the two only known baryons who have a mean lifetime of more than a second. However, we know, that there is big number of further baryons. Most of them include quarks of higher generations, which is why they are generally more energetic, less stable and naturally occur incredibly rarely.

Mesons

The second type of Hadrons is called mesons. They always have an integer spin and are thus bosons. Mesons are very unstable, hence they have mean lifetimes of fractions of seconds, and almost only occur during high-energetic particle collisions, like the decay of cosmic rays. Generally, they are composed of two quarks: one normal quark and one anti-quark.
As the baryons, they interact with the four fundamental forces: strong interaction, weak interaction, gravity and, if charged, electromagnetism.
The most common meson is the pion.

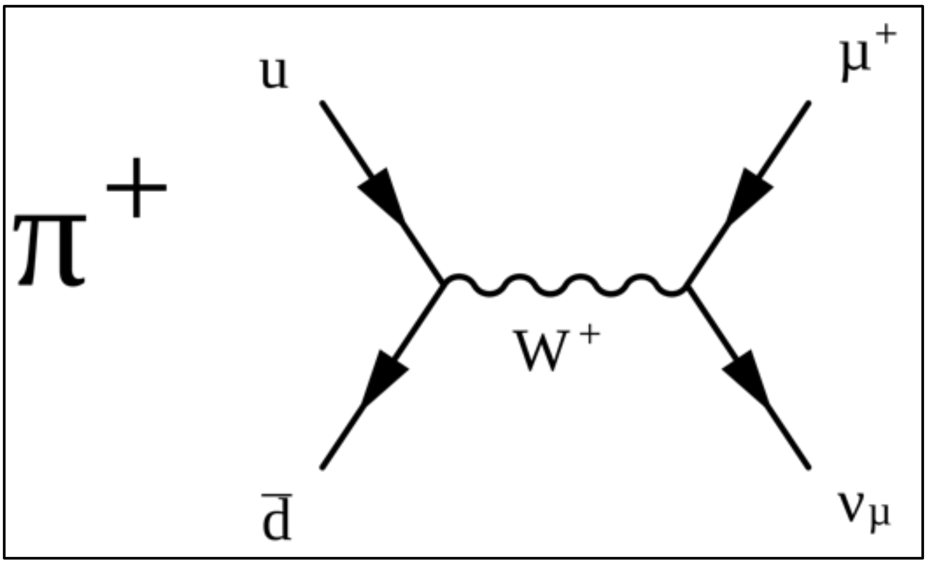
Pion

The pion is the lightest of the hadrons. The symbol of a pion is π. Pions occur very often in cosmic particle decays. A pion is actually the name for these three particles: the positively charged pion π^+, the negatively charged pion π^- and the neutrally charged pion π^0.
The π^+ is composed of an up-quark and an anti-down-quark ($u\bar{d}$). The electrical charge is thus: $Q(\pi^+) = Q(u) + Q(\bar{d}) = +\frac{2}{3}e + \frac{1}{3}e = 1e$.
The π^- is actually the antiparticle of the π^+. That means that the quarks of the π^- are the antiquarks of the π^+. Therefore, the composition is $d\bar{u}$. We can prove with the electrical charge: $Q(\pi^-) = Q(d) + Q(\bar{u}) = -\frac{1}{3}e - \frac{2}{3}e = -1e$.
The last of the pions is the neutrally charged π^0. It is its own antiparticle. Generally, you can say that it is either made up of an up-quark and an anti-up-quark ($u\bar{u}$) or a down-quark and an anti-down-quark ($d\bar{d}$). However, this particle is more complex. As I already mentioned, these particles aren't spheres flying around, but are blurs of influence. Therefore, considering every factor of influence a π^0 and its composition, a π^0 has actually a quark content of $\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$.
This is notation of the vector force this particle has.
The π^+ and the π^- have incredibly short mean lifetimes of $2{,}60133 \pm 0{,}0005 * 10^{-8}\ s$. However, the π^0 has an even shorter mean lifetime of $8{,}4 \pm 0{,}6 * 10^{-17}\ s$.

Another pretty common meson which also occurs in cosmic radiation is the kaon. As the pion, it exists in three different electrical states: K^+, K^- and K^0. The only substantial difference is that the Kaon contains the second generation strange-quark. Their compositions are respectively: $u\bar{s}$; $s\bar{u}$; $d\bar{s}$ or $s\bar{d}$. Hence, they are less stable and more energetic.

Weak interaction and Feynman diagram

Almost every particle eventually decays. This happens due to weak interaction and its bosons: the W^+, the W^- and the Z^0.
Besides, it is the only interaction which has the ability to change the flavour of quarks. A down-quark for example can emit a W^- boson and become an up-quark. This is why radioactive decay of neutrons into protons is possible.
The most important function of the weak interaction, concerning cosmic radiation is the following. Here is an example of a decaying π^+.



A π^+ is composed of an up-quark and an anti-down-quark. When the pion decays, those two quarks are destroyed and emit a W^+ boson. This highly energetic boson decays almost immediately into an anti-muon (μ^+) and a muon-neutrino. Exactly this process is represented in the so-called 'Feynman diagram' here at the left. Important to say about this diagram is that the time-axis generally passes from left to right. Moreover, a straight line represents a particle and wavy lines always represent bosons of the weak interaction. Furthermore, the arrow-shape does not indicate in which direction the particle moves but whether the particle that the line represents is a fermion or an anti-fermion. In this diagram, we can see for example, that the arrow on the line of the anti-muon μ^+ is pointed against the passing of time, hence an anti-fermion. The same applies for the anti-down-quark.
The decay of the secondary cosmic ray particles works in a very similar way.

Primary Particles

Cosmic radiation is a radiation, consisting of high-energy particles, circulating through space. The energy of these particles can reach astonishing values of up to 10^{20} eV. This radiation mainly consists of the following particles:

- 89 % Protons
- 10 % Nuclei of Helium (2 Protons; 2 Neutrons)
- 1 % Heavier atomic nuclei: these nuclei can be of every naturally occurring element on the periodic table. The heaviest nuclei of those nuclei with the most protons in it (92) is uranium.

These particles originate from high-energy events in deep space. There, they are accelerated to speeds close to that of light. After traveling astounding distances, some of them hit Earth.

Origins

The origin of these highly energetic particles is still rather unclear. Firstly, this is due to the fact that on the Earth's surface, we are only able to detect the secondary particles. These secondary particles can't give us a directional indication, from where the primary particle came. Furthermore, even if we were able to detect primary particles and were able to find out from which direction they came, their origin would still be unclear. That's because there are giant magnetic fields through the whole space, which can affect the cosmic radiation's path. Due to the incredible vastness of space, only very slight deflections can completely change the particle's path. Therefore, we can mostly only theorise from where the cosmic rays are coming. One method is of course, due to the understanding we have about interstellar bodies, we can predict that they probably emit some form of cosmic radiation. Furthermore, we can correlate different observations with higher muon flux. If we measure for example on a day a lot of cosmic radiation and we observed a highly energetic extraordinary event during the same time, there is a high probability that the cosmic radiation originated from that event. Using these methods, we predict that cosmic rays have three main origins:

Solar Flares

One of the main origins of cosmic radiation is the Sun. When magnetic fields, which are caused by permanent interactions of particles on the Sun's surface, align in a specific way, a solar flare occurs. This is a process where the plasma (highly conductive gaseous state of matter), generally near the sunspots, is heated to tens of millions of Kelvin. This causes electrons, protons and heavier nuclei to be accelerated to near the speed of light and electromagnetic waves over the whole spectrum are emitted. The accelerated particles are now what we call primary cosmic radiation. Solar flares can accelerate the particles to energies up to 100 MeV. Even though that is an enormously high value, it is still the weakest source of the cosmic rays.

Supernovae

Stars are essentially giant spheres of gas. Consequently, they should collapse due to their own gravity. However, this does not happen, because there is a force counteracting gravity called radiation pressure. This force is the result of a process called stellar fusion: The core of a young star is a hot and dense concentration of Hydrogen atoms, the lightest element in the universe. Due to permanent collisions between these Hydrogen atoms, they can fuse together to the second element on the periodic table. After a long time, the Hydrogen will run low. This means, the core will get hotter and denser, which allows the Helium to fuse to Carbon. This process repeats itself until only Iron is left. It isn't possible to fuse these atoms in these conditions. Depending on the size of the star, it already isn't possible anymore to fuse lighter atoms. Our sun for example can only go to Carbon. This stellar fusion creates the radiation pressure, which counteracts gravity. Intuitively, when stellar fusion stops, there is nothing anymore which prevents the star from collapsing. This collapse results in a giant explosion called supernova. Depending on the mass of the star, this supernova leaves behind dwarfs (inactive very dense matter), neutron stars (so dense material, that electrons and protons are packed together and form neutrons), or black holes. During the supernova, particles are accelerated to incredible speeds. They can reach energy values from 100 MeV to 10 GeV. Supernovae are probably the origin of most cosmic rays hitting our atmosphere.

Quasars

Quasar is a term to describe the active centre of a galaxy. This name is derived from 'quasi-stellar radio source'. This means that a quasar is a starlike source of electromagnetic waves in the radio spectrum. Generally, these quasars consist of a black hole, with matter orbiting it. Matter falling in this black hole creates extreme energies accelerating particles to up to incredible energies of 1011 GeV. The particles originating from quasars are by far the most energetic cosmic rays. However, the exact process how these particles are accelerated are still a mystery.

Secondary Particles

When primary particles of the cosmic radiation hit the molecules in the Earth's upper atmosphere, a cascade of secondary particles is created. One single particle can create cascades of secondary particles stretching over 40 km^2 and consisting of millions of particles. This involves a multitude of collisions and decays.

The Cascade

When a primary particle, i.e. single protons or atomic nuclei, hits a molecule in the upper atmosphere, a nuclear spallation reaction occurs. Spallation reactions are basically the following process: A proton or any other atomic nucleus collides with another. Due to this collision a variety of secondary particles is created:
Generally, the most common particle resulting from this collision is the pion. Less commonly, light baryons (neutrons/protons) or even kaons can occur.

Due to the instability of the pions, they decay pretty fast. This happens around 10 – 15 km of altitude. However, charged pions and neutral pions decay very differently.

With a probability of 99,99%, the charged pions decay into muons and muon neutrinos:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

As already explained, this happens due to the following phenomenon. The decay of the two quarks in the pion emit a W boson. This boson almost immediately decays into a muon and a muon neutrino. Depending on the charge of the initial pion, the charge of the W boson changes and the ones of the muon and the neutrino.
However, there is a slight chance that they decay into lower energy particles:

$$\pi^+ \rightarrow e^+ + \nu_e$$
$$\pi^- \rightarrow e^- + \bar{\nu}_e$$

The neutral pions π^0 usually simply decay into two photons:

$$\pi^0 \rightarrow \gamma + \gamma$$

Nevertheless, there is chance of 1,2% that they decay into a photon, an electron and a positron.

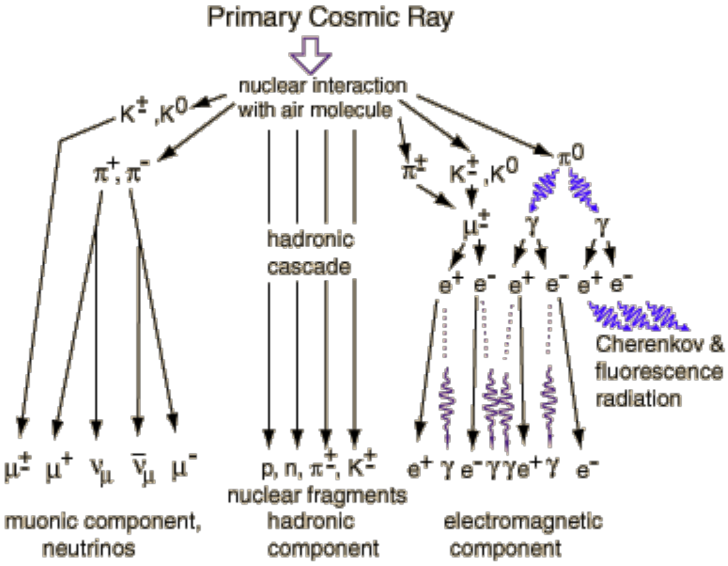
$$\pi^0 \rightarrow \gamma + e^+ + e^-$$

Pair production, which I will later explain, is responsible for transforming photons into electrons. There are also decays which transform electrons into photons.

The Kaons decay most commonly into muons and muon neutrinos (about 60%) or into different pions, which once again decay into muons and muon neutrinos, respectively into photons and electrons.

Summarising, the whole cascade can be divided into three sections. The leptonic component, the hadronic component and the electromagnetic component. The leptonic component starts with kaons and charged pions, which decay to muons and neutrinos and their respective antiparticles. The second component is the hadronic component. It basically contains hadrons which didn't decay before reaching the surface. The third and last section is called electromagnetic component. It starts with Kaons and pions, which either directly decay to photons or electrons, or decay to muons which decay due to energy loss to electrons. In the

electromagnetic component, the electrons, the photons and the positrons decay over and over again into each other.



Due to the instability of most of these particles, the majority of these particles reaching the surface of the Earth are the muons, the neutrinos, and the electrons. Electrons however are rather uninteresting, because it is a very common particle. Furthermore, neutrinos almost do not interact with any matter, due to their low energy and neutral charge. This makes them more difficult to detect. The muon, in contrast, interacts pretty often with matter. This implies correlation with climate parameters and easier detection. This makes them the most interesting secondary particle of the cosmic radiation.

Muon: Secondary Cosmic Ray

The muon is the second-generation particle of the electron. It is about 207 times heavier than its ‘light brother’. Moreover, it is one of the most interesting secondary particles of the cosmic radiation. In the cascade, it derives of the decay of pions and kaons. The creation process happens around 10 to 15 km of altitude and they travel at speeds very close to that of light.

Temporal Dilation and Half-lives

A muon has a half-life at rest of 1,56 µs. They travel at 0,98 times the speed of light. They are formed at around 10 km. We can calculate the time a muon needs to cover this distance:

$$T = \frac{10\ km}{0{,}98\ c} \approx \frac{10\ km}{0{,}98 * 0{,}3 \frac{km}{\mu s}} \approx 34\ \mu s$$

This would theoretically mean, that until muons reach the surface, $\frac{34}{1{,}56} = 21{,}8$ half-lives would have elapsed and therefore only $\frac{1}{2^{21{,}8}} \approx 0{,}00000027$ times the initial particles would be left. Out of a million particles, only 0,27 would reach the surface. This however isn’t right. Time dilation is at play. Special relativity, the world-famous theory of Albert Einstein, says that objects at the speed of light experience time much slower than an outside observer. The equation for time dilation is

$$T' = \frac{T}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

, where:

- T’ is the amount of time the outside observer experiences
- T is the amount time the moving object experiences
- v is the speed of the moving object
- c is the speed of light

Hence, we can calculate the half-life of muons moving at $0{,}98\ c$ for an outside observer:

$$T' = \frac{1{,}56\ \mu s}{\sqrt{1 - \left(\frac{0{,}98\ c}{c}\right)^2}}$$

$$T' = \frac{1{,}56\ \mu s}{\sqrt{1 - 0{,}98^2}}$$

$$T' \approx 7{,}8\ \mu s$$

For a muon which travels at $0{,}98\ c$, the half-live for an outside observer lies around 7,8 µs. So, when travelling 10 km, $\frac{34}{7{,}8} = 4{,}36$ half-lives of a muon elapse. Hence, we can calculate that after 4,36 half-lives only $\frac{1}{2^n} = 0{,}049$ times the initial amount of the muons remain. In conclusion, we have thus 49’000 muons remaining muons of 1’000’000 initially formed ones. In detecting muons, we actually prove time dilation because if time dilation didn’t exist, almost no muon would arrive at the surface of the Earth.

Atmospheric Interactions

During its trajectory through the atmosphere, the muon experiences multiple interactions, resulting in constant energy loss. If the muon loses enough energy, it can decay. Therefore, these interactions also correlate with the muon flux on the Earth's surface. Every muon at an energy below 1 TeV loses energy through a process called ionisation. At higher energies, they can initiate stronger processes.

Ionisation

The muons interact with the electrons of surrounding atoms, losing a minimal energy, although enough to loosen an electron from its nucleus. Due to this process, the matter along the muon' s trajectory gets ionised and the muon loses energy continuously. Ionisation doesn't only happen in the atmosphere but also occurs in every other material. Generally, the more dense the material, the more energy the muon loses traveling through it.

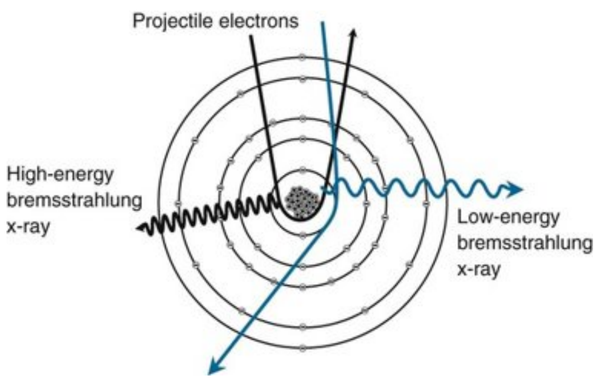
This process has a very important implication: Temperature has an effect on the cosmic muon flux.

The effect of the temperature on muons is conclusively caused by their interaction with present atomic nuclei in the atmosphere. An augmentation of nuclei in the atmosphere, thus a rise of temperature can have two effects: Firstly, more pions will form, therefore more muons derive of their decay. Secondly, however, a rise of temperature between winter and spring causes an expansion of the atmosphere, which is why pions arrive at a higher altitude. Accordingly, the muon's trajectory gets longer, decreasing muon flux at sea level, because more muons decay due to ionisation. Patrick Blackett, a British experimental physicist known for his work on cloud chambers and cosmic rays, understood that dependence on atmospheric pressure (and therefore as already mentioned temperature) is decisive. He found that actually muons are formed when the atmospheric pressure has a value of around 100 mbar, which can be defined as an atmospheric layer whose height is determined by the temperature. All this leads to the conclusion that the muon flux on the earth's surface decreases significantly in the months of summer, because the 100 mbar layer is at a higher altitude, making the journey longer for the arriving muons.

One of the studies I realised during my year at the Astronomie focuses mainly on this process. We proved that the muon flux changes accordingly.

Bremsstrahlung

The phenomenon of 'Bremsstrahlung' is the following: The muon interacts with a strong electromagnetic field, which can be natural (the electric field of a nucleus) or man-made (the magnet field in a particle accelerator). Electrons and positrons, are due to their high speeds very easily affected by these fields, as are their higher-generation particles, the muons. During this interaction, the muon emits a photon that carries away part of its energy, hence energy loss. The muon is thus slowed down, and its trajectory modified.



This is actually the reason why particles in accelerators lose energy continuously. They are subjected to strong electromagnetic fields in order to keep them on their trajectory. This causes conclusively constant energy loss.

Pair production

Pair production is essentially the creation of a particle – antiparticle pair from a neutral boson. Generally, when speaking of pair production, one refers to the creation of an electron positron pair from a photon. This always happens near an atomic nucleus. This is the dominating process in the electromagnetic component of the cascade. However, this process needs incoming energy to be initiated. This is where the muon comes at play. Because an amount of energy of the muon is used to initiate pair production, the muon loses energy. For muons with energies of over 1 TeV, this is actually the main reason why muons lose energy. The muons continue to sustain the electromagnetic cascade along their whole trajectory.

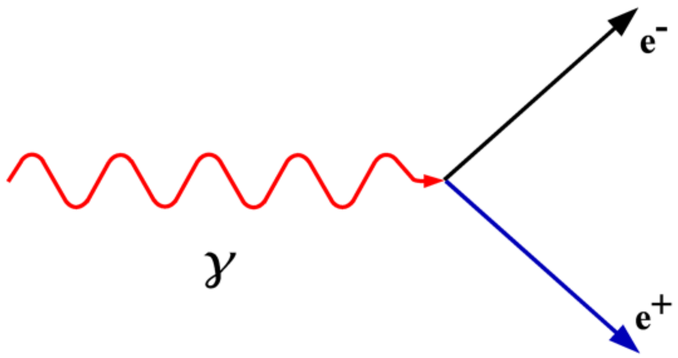


Photo-nuclear interactions

Very rarely, a specific interaction between a muon and an atomic nucleus can happen. This can only happen with muons with energies of more than 10 TeV. The muon basically collides with the nucleus transferring a big amount of energy to the nucleus. In standard rock for example, the muon can lose 10 % of its energy.

Cosmic Radiation – Practical Studies

Since end of 2017, we are realising practical studies about cosmic radiation in the *Entreprise LEM.SCIENCE Astronomie*. Our workgroup consists of 7 students, and our supervisor Mr. GRANA Andrea. We measure the flux of the muons and do various experiments to study how different parameters can affect these particles.

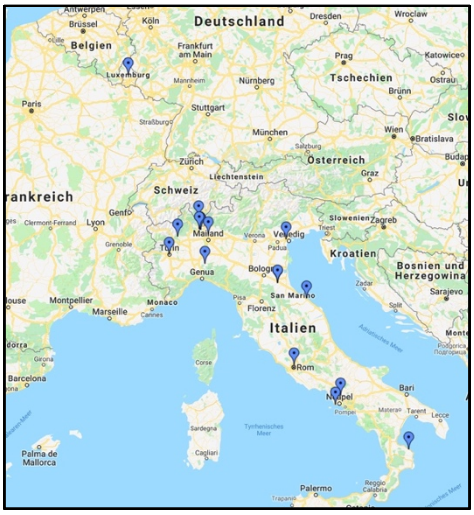
I did some substantial work to contribute to this project. Aside from a specific study and really much data analysis, I created a software, which spares months of works. Furthermore, I extended my project from my previous Travail personnel (Pyranometer), to a fully equipped weather station, which we use now in our work group as main information source for climate parameter.

In the following, I will describe our project in general and describe our detector. Furthermore, I will specifically talk about my practical projects. Finally, I will shortly talk about the specific study about the Blackett Effect I realised and list other studies to which I contributed in some way.

Project and Instrumentation

ADA project

To realise this study, we used a particle detector, the AMD5 (Astroparticle Muon Detector), which was designed as part of the ADA project (Astroparticle Detector Array). ADA is an educational project designed to detect cosmic rays. The structure of the network is comparable to that of the professional cosmic ray observatories. Individual detectors are distributed throughout the national territory and beyond to schools, associations and private astronomical observatories. ADA was developed with the intention of promoting astroparticle physics and making it accessible to everyone. Furthermore, ADA is an interesting field of research not only for teachers, but also for independent committed scientists.

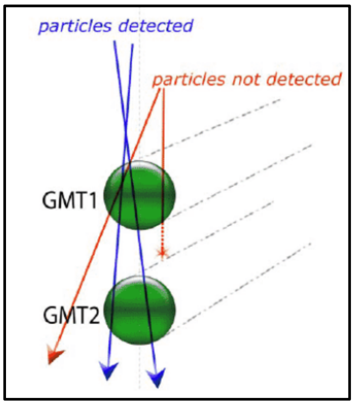


As of this moment (April 2019), the ADA detectors are mainly distributed through Italy. There is also one detector in Switzerland, just on the border to Italy. Thus, we at the LEM are the only ones further away from Italy. Therefore, our results are very interesting to the Array because the climate parameters are very different in Luxembourg.

All the data collected by this array is accessible for free on the website of ADA: https://www.astroparticelle.it.

AMD5 Detector

The AMD5 detector is a particle detector that counts muons. Basically, it consists of two 10.8 cm long and 1 cm wide cylindrical Geiger-Müller counter tubes (for short also GMT, Geiger-Müller tube) of the SBM 20 model, one above the other. This model, which works with a mixture of the noble gases (neon, argon and bromine), was originally produced in the 80s and 90s in the Soviet Union in large quantities. Today they continue to be produced in all ex-Soviet countries. The reaction time

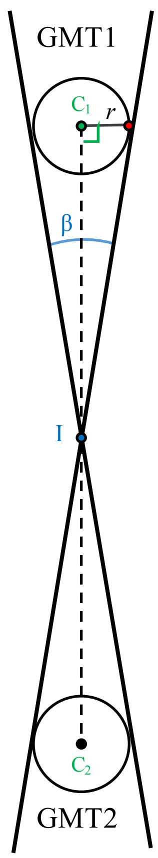


of the gas mixture is 190 μs. The SMB 20 model is one of the few to have electronic features. Therefore, the same technology is still being used in today's GMTs. The AMD5 detector measures muons, which arise during high energetic events and therefore have very high energies, which exceed the energy of radioactive radiation by far. Thus, they are the only particles that can pass through two Geiger-Müller tubes almost simultaneously. The counter further along the GMT detectors only counts the events where there is a "coincidence". In other words: The counter needs a signal from both GMTs almost simultaneously (within a short time). With the AMD5, the time in which both GMTs must have sent a signal to create a coincidence is fixed at 66 ms and serves to exclude the majority of particles that are not cosmic rays.

The detector also has 3 LED lights: one for each GMT (lights up briefly on a signal) and the third in the case of a coincidence.

The detector is constantly connected to the computer, which saves all the measurements. The measured data can be graphically displayed using the "AstroRad" program, which came with the detector.

Based on the fact that the diameter of the GMTs is of about 11 mm and that they are 6 cm apart from each other, we can calculate that we have a measuring angle of about 18°.



Calculation of the measuring angle β

- Calculation of the GMT radius

$$r = \frac{d}{2} = \frac{11\text{ mm}}{2} = 5.5\text{ mm}$$

- The distance between the two centres is the sum of the distance that they are apart from each other and two times the radius:

$$\overline{C_1C_2} = 60\text{ mm} + 2r = 71\text{ mm}$$

- The distance between the centre of one GMT and half the distance between the GMTs

$$\overline{IC_1} = \frac{\overline{C_1C_2}}{2} = \frac{71\text{ mm}}{2} = 35.5\text{ mm}$$

and the radius r now forms both sides of the right-angled triangle with:

$$\tan\left(\frac{\beta}{2}\right) \cong \frac{r}{D/2} = \frac{d}{D} = \frac{5.5}{35.5} = \frac{11}{71}$$

$$\Leftrightarrow \quad \frac{\beta}{2} \cong \arctan\left(\frac{11}{71}\right) = 8.8068°$$

- The measuring angle is thus approximated:

$$\beta \cong 2 \cdot 8.8068° = 17.6°$$

So: $\beta \approx 18°$

Custom Support Software

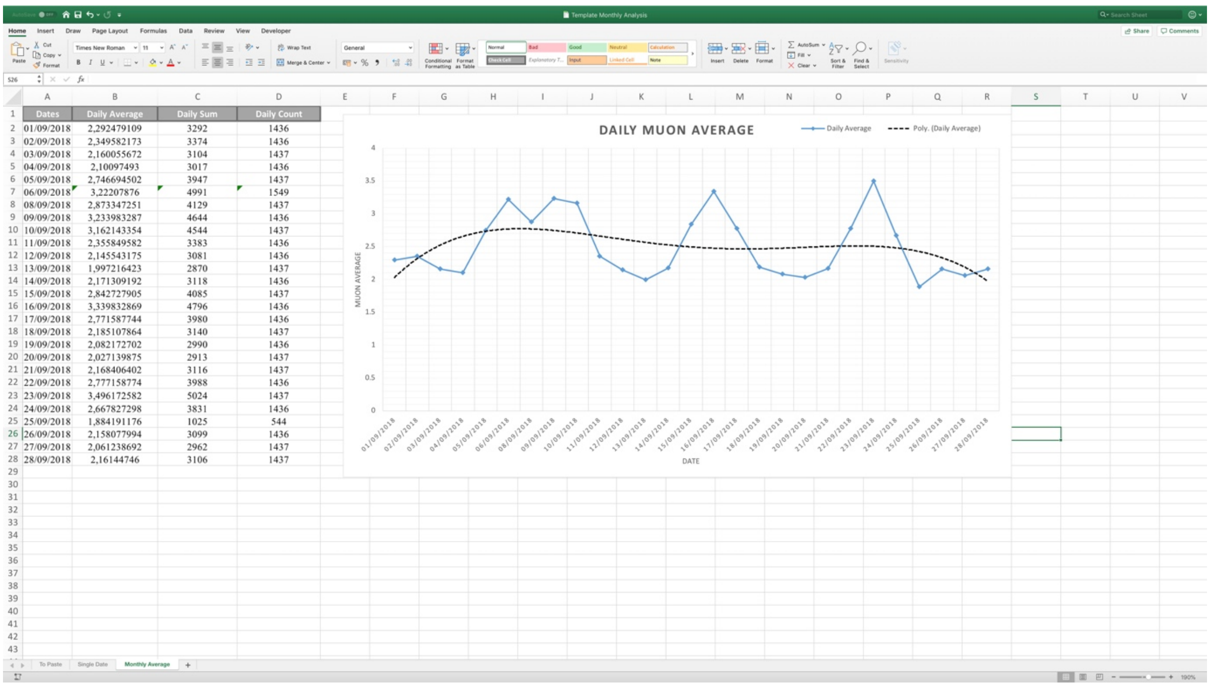
The AMD5 detector came along with a software called AstroRad. The software is used analyse the data measured by the detector. However, the software's main purpose is to survey the live data from the detector, meaning that long-term analysis isn't possible with AstroRad. Furthermore, normally, every participant of ADA opens a remote access to the computer to register the data for the ADA-Team. This was not possible for us because our school's IT policy would not allow it. Therefore, for almost a year, we weren't connected to the global AMD-Data-Archive and we had to get the data with Flash Drives or even with external Hard Drives. With a long, time-wasting and stressful procedure, we had to prepare the data for analysis in Microsoft Excel spreadsheet. The first step to facilitate the data analysis was to reduce the time we needed to process the little data. That's why I created a website which could do multiple weeks' worth of work in only a couple of minutes.
Normally, a website is a bad choice for software processing with a lot of data, but as it isn't possible to install and run custom programs on our school's computers due to the IT policy, plus, everyone could immediately access it and little updates are easily made too, a website was the easiest choice. The raw data-files coming from the detector can be uploaded with three different options now being possible:

1. <u>Daily data table</u>

In the first section, a table can be rendered which shows the daily average and daily sum of every file that was uploaded.

2. <u>Data Preparation for MS Excel</u>

In the second section too, a table is created, but this one is supposed to prepare the data of the uploaded files for in-depth-analysis in Microsoft Excel. We also have a pre-prepared Excel workbook that is programmed to receive the data copied from this section and process it automatically. Also, a chart is generated. On the last sheet, it is possible to see the exact data from a chosen day. Some VBA-Code is included in this workbook to make it work.
The final result is this table and chart. This is completely automatically generated as soon as the giant amounts of raw data is properly entered.

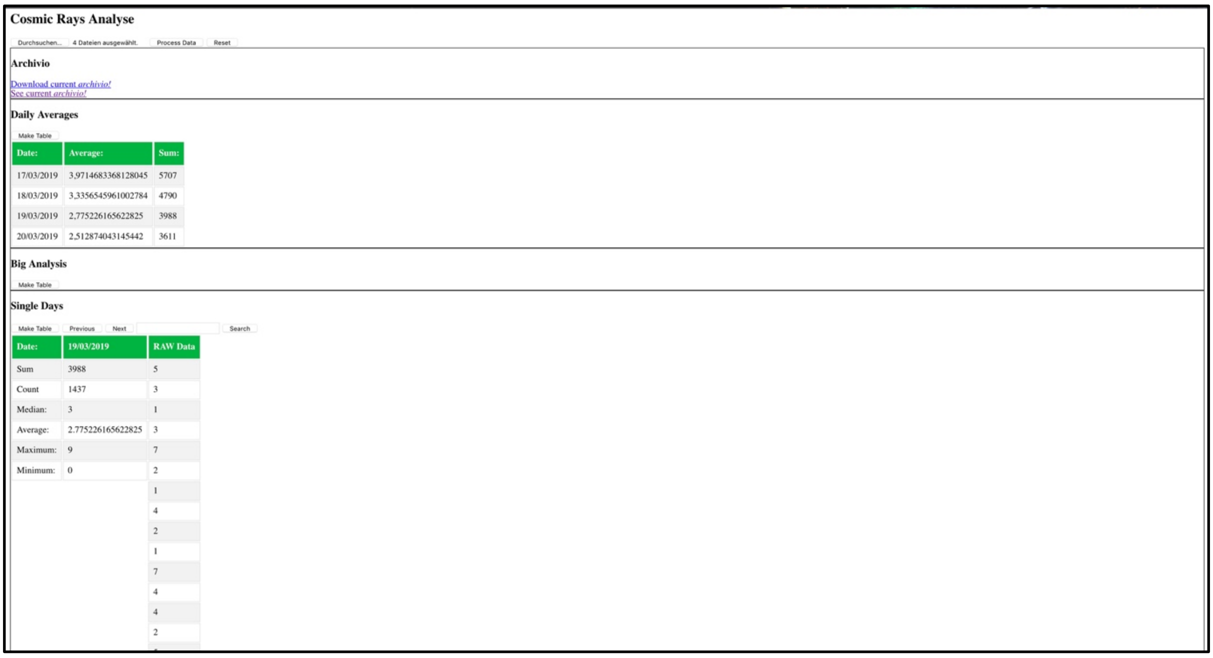


Dates	Daily Average	Daily Sum	Daily Count
01/09/2018	2,292479109	3292	1436
02/09/2018	2,349582173	3374	1436
03/09/2018	2,160055672	3104	1437
04/09/2018	2,10097493	3017	1436
05/09/2018	2,746694502	3947	1437
06/09/2018	3,22207876	4991	1549
08/09/2018	2,873347251	4129	1437
09/09/2018	3,233983287	4644	1436
10/09/2018	3,162143354	4544	1437
11/09/2018	2,355849582	3383	1436
12/09/2018	2,145543175	3081	1436
13/09/2018	1,997216423	2870	1437
14/09/2018	2,171309192	3118	1436
15/09/2018	2,842727905	4085	1437
16/09/2018	3,339832869	4796	1436
17/09/2018	2,771587744	3980	1436
18/09/2018	2,185107864	3140	1437
19/09/2018	2,082172702	2990	1436
20/09/2018	2,027139875	2913	1437
21/09/2018	2,168406402	3116	1437
22/09/2018	2,777158774	3988	1436
23/09/2018	3,496172582	5024	1437
24/09/2018	2,667827298	3831	1436
25/09/2018	1,884191176	1025	544
26/09/2018	2,158077994	3099	1436
27/09/2018	2,061238692	2962	1437
28/09/2018	2,16144746	3106	1437

3. <u>Single Days – Exact</u>

In the third and last section, a table with the single datasets, median, average, sum and further details is generated for a day. At the top you can chose different dates.

In the following picture, an example is shown where the website generated the Daily Averages and the Single Days sections. Please note that this website has a purely productive function and almost no design adjustments were made.



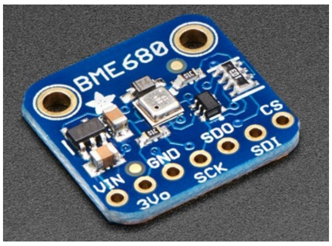
To gain a perspective of how much time this saves, here an example: For the picture above, I needed about two minutes. Without this website I would probably have needed at the very least a quarter of an hour to do the same work. Furthermore, it doesn't take more time with the website to process much more data. In contrary, we lose very much time for every additional day.
We can conclusively focus much more on studying the data because we waste less time processing it.
The code of this website can be found in the attachment (CosRayAnalyse.html). Furthermore, it is accessible online under : https://www.lem.codes/users/luich893/CosRayAnalyse.html.

The problem with the data processing was solved with this website and the Excel sheet. However, we still had to copy the data to Flash Drives to access it. In October I found out that FTP (File Transfer Protocol) isn't actually disabled on our school's network. It didn't take long until the following system was working:
Every day at 1:00 AM, a simple Windows Batch script runs on the computer and uploads the whole data archive after zipping it via FTP on a school server. (Attachment → upLoadScript.bat) Furthermore, it opens the website extractor.php, whose PHP-Script unzips the uploaded data on the server and deletes the old archive (Attachment → extractor.php).
On the computer, a second script runs every five minutes which uploads the daily-data.txt file. It shows all the data from the current date. The file itself updates every minute (Attachment → dailyDataUp.bat).
I created another website to list the whole archive. It is a simple list, where you can access the single files and download a selection of these files (Attachment → archiveList.php). I

created a stand-alone PHP-Script to create ZIPs and stream them to the clients to download the selected files (Attachment → downloader.php).
When we finally went completely online, we could send the archive directory link to ADA, who can now access it and add it to their AMD-archive on their official website.

Weather station

In addition to our AMD5 detector, we wanted our own weather data because there are many different relationships between muon flow and climate conditions. Therefore, we set up a simple weather station in the backyard of our school. It continuously measures temperature, air pressure, humidity and solar radiation. It consists of a Raspberry Pi, an Adafruit BME680 sensor, a SPLite2 Kipp&Zonen pyranometer, an Adafruit ADS1015 chip and a DS3231 Precision Real Time Clock.
The Adafruit BME680 sensor is a sensor for measuring temperature (±1°C), humidity (±3%) and air pressure (±1hPa). It was developed by Adafruit (based on a BOSCH sensor) and I set it up for data transfer via the I2C protocol.
The compact pyranometer SPLite2 from Kipp&Zonen has a silicon photodiode and is used worldwide. It only has a spectral response from 400 to 1100 nm, but for us that's more than enough. It is also very resistant to extreme weather conditions.



Since the data output of the SPLite2 is not digital but an electrical voltage, we needed the Adafruit ADS1015 chip to convert the value of this voltage into a digital signal. Communication is also via I2C.
To make sure that the Raspberry Pi's system date doesn't change, we finally added the DS3231 Precision Real Time Clock. It is another extension that communicates via I2C and is essentially an overlay for the built-in clock in the Raspberry. The DS3231 has its own power support.

Since it wasn't possible to have an active Internet connection at the location we wanted, we set the Raspberry Pi to act as a stand-alone network and host a W iFi network. So, we can get the data by connecting to this WiFi.
The data is collected with two Python scripts that store it in a local MySQL database, triggered by a cronjob.
The first script collects the data from the BME680 sensor. It can be found in the appendix under BME680DataCollect.py. It doesn't execute many extraordinary steps, but there is one longer calculation. The sensor only measures the absolute air pressure, but usually the relative air pressure is used. This is a value that indicates what pressure would be measured at sea level, but in exactly the same weather conditions. Several calculation steps are required to convert this value.
The second script collects the data from the pyranometer by reading the ADS1015 chip, which is directly connected to the pyranometer. Since the ADS1015 chip only provides bits as output, we have to do some calculations:
When the gain of the ADS1015 is set to 16, the range of the chip is as follows:

$$-256mV \leftrightarrow 256mV$$
$$-32768B \leftrightarrow 32767B$$

That means to convert from Bit to Volt, we have:

$$\frac{256mV}{32767B} \approx 0{,}007813\frac{mV}{B} = 7{,}813\frac{\mu V}{B}$$

The formula to calculate the solar irradiance is:

$$S_{irr} = \frac{0_{vol}}{S_{ens}}$$

where S_{irr} is solar irradiance, 0_{vol} is output voltage and S_{ens} the sensitivity of the pyranometer. Conclusively, we have a linear function:

$$S_{irr}(x) = \frac{x * 7{,}813\frac{\mu V}{B}}{10{,}1\frac{\mu V}{W/m^2}} \Leftrightarrow S_{irr}(x) \approx x * 0{,}7735\frac{W}{m^2 * B}$$

where x is the measured Bit value from the ADS1015. It only has to be multiplied by $0{,}7735$ to obtain the solar irradiance. This script too can be found in the attachment under SPLite2.py.

By now, we actively use this data to support our studies.

Studies

Apart from these two rather practical projects, I also contributed work to some specific studies at the 'Astronomie'.
Firstly, I worked with STEVENS Noah on a study about the Blackett Effect. It is about the correlation between the cosmic muon flux and the seasonal variation of climate parameters. I talked about this effect in the theoretical part of this Travail personnel. Our final scientific paper is in the attachment.
Secondly, I participated with a group of two other students at the national science contest 'Jonk Fuerscher'. For this purpose, we created a paper which treats both the Blackett Effect and the Weather Effect, another study realised in the 'Astronomie'. I included it in the attachment. We also designed a poster for the presentation. A scaled-down version is included in the attachment too.
Finally, a great deal of scientific papers were written with the help of my data analysis software or my manual data analysis. Some of the papers haven't been translated to English, which is why some of them are in French. Due to the fact that some of these studies aren't finalised, I cannot show all of them, but some of the finished papers are included in the attachment. I chose these three:

- Étude de la variation de l'intensité du flux de muons cosmiques mesuré avec le détecteur AMD5 durant l'année 2018
- Analysis of the weather conditions effect based on the detected cosmic muon flux with the AMD5 detector
- Étude de l'effet zénith sur la base du flux de muons mesuré avec le détecteur AMD5

Conclusion

During my research for this 'Travail Personnel', I learned so incredibly much, that I often had trouble choosing what was important and what wasn't for my work. Often, when I only wanted to look up a single term, I suddenly read about completely different branches of particle physics. This showed me again that physics is so incredibly diverse. I really had fun learning about all these different branches, and it confirmed for myself that I want to continue on the path of physics.

Moreover, the programming part of this work was also very interesting. I learned some more about the programming language and the additional experience also proved already very useful for another project I am currently working on (public website, processing and analysing data of bee hive conditions). One of the main reasons I enjoy programming is the satisfaction knowing that a few lines of code I wrote can easily save you an incredible amount of work and time.

In conclusion, I can definitely say that physics is the way to go for me. I will of course continue studies concerning cosmic radiations. I will also continue some programming projects in order to facilitate our research even more. Furthermore, some incredibly interesting possibilities already opened up for different future projects in the sector of physics that I really look forward to.

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- http://lappweb.in2p3.fr/~maire/tutorials/muonNuclear.pdf
- Previous work on Cosmic Radiation
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Pictures

- https://upload.wikimedia.org/wikipedia/commons/0/00/Standard_Model_of_Elementary_Particles.svg (Table of Standard Model; p. 6)
- https://simple.wikipedia.org/wiki/File:Bosons-Hadrons-Fermions-RGB-pdf.pdf (Composite Particle Groups; p. 9)
- https://upload.wikimedia.org/wikipedia/commons/6/69/PiPlus_muon_decay.svg (Pion Decay; p. 11)
- https://upload.wikimedia.org/wikipedia/commons/e/e3/Magnificent_CME_Erupts_on_the_Sun_-_August_31.jpg (Solar Flare; p. 12)
- http://www.ox.ac.uk/sites/files/oxford/styles/ow_medium_feature/public/field/field_image_main/Supernova.jpg?itok=4XfLJS08 (Supernova; p. 13)
- https://upload.wikimedia.org/wikipedia/commons/thumb/3/38/Artist%27s_rendering_ULAS_J1120%2B0641.jpg/1200px-Artist%27s_rendering_ULAS_J1120%2B0641.jpg (Quasar; p. 13)
- http://ansnuclearcafe.org/wp-content/uploads/2011/08/cosmic-ray-cascade-chart.gif (Cascade; p. 15)
- https://upload.wikimedia.org/wikipedia/commons/a/a5/Pair_Production.png (Pair production; p.18)
- Screenshot:https://www.google.com/maps/d/viewer?mid=1YCp3AGNY8bkUDTiqxsjoI2J7PY4&ll=44.851182077618816%2C11.534543750000012&z=6 (Map of ADA; p. 19)
- https://cdn-shop.adafruit.com/970x728/3660-00.jpg (BME680; p. 23)
- https://www.ecotech-bonn.de/uploads/product_images/96ab2d1780440e34fe825e3f62376c626542dccd.jpg (SPLite2; p. 23)

Attachment

Software Code

Attachment

Scientific Articles