Muons

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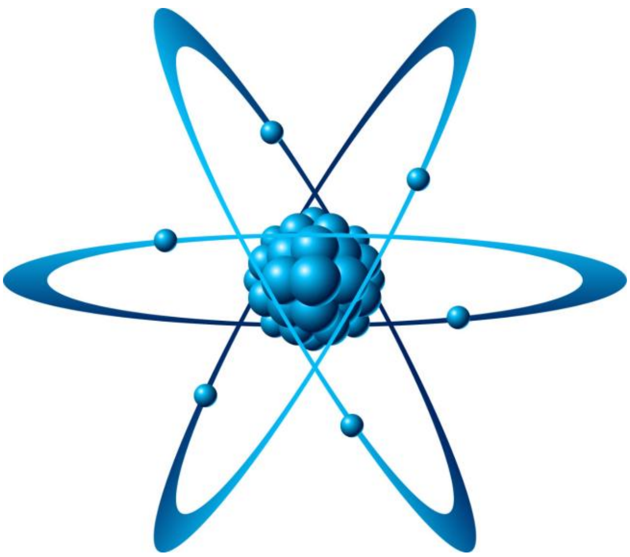


Table of contents:

Introduction

Man has been trying to understand the universe since it was created. First of all, people tried explaining things they didn’t understand by assigning a divine power to it. Years later, people started understanding things better, especially the ancient greeks, arabs and chinese took a great part in this. After the fall of the church people started conducting alchemy and later on physics. Great scientists, such as Newton, Mendeleev and Einstein started explaining the world around them using formulas and elements. Now, in the 21^{st} century, people are still trying to understand everything that exists in the universe. Experiments are done all over the world, with or without succes. In this profielwerkstuk, a small part of the universe will be explained: the muon. Found in 1936 by Carl D. Anderson and Seth Neddermyer, it was one first basic particles found after the proton, neutron and electron. It has helped us understand the universe a little bit better, aiding in the creation of the Standard model and in understanding the world of space-time. A seemingly useless particle because of it’s lifetime, but it has helped us back then and will help us in the future. After having heard of the muon, I immediately wanted to know more about it. With the help of some people at the University of Leiden, including the supervising teacher, I was able to do some research and measurements, finally creating this PWS. This PWS covers the detection of muons, their source, their life and their uses.

Chapter 1: What is a muon?

Paragraph 1.1: Particle physics for dummies

To understand what a muon actually is, let's first take a look at some particle physics. Everything is made out of molecules, which on their turn are made out of atoms. Atoms are made out of 3 types of particles: Protons, with a positive charge and Neutrons, without charge make up the the core of the atom. Around the core of the atom is a cloud of smaller particles, the electrons, with a negative charge. For quite some time, scientists believed those 3 particles to be the smallest particles to exist. However, in 1968, scientists proved that protons and neutrons were not in fact elementary particles. Protons and neutrons are both build up out of 3 smaller particles, which scientists do believe to be elementary particles: quarks. The proton is made out of 2 up-quarks and 1 down-quark, while the neutron is made out of 1up-quark and 2 down-quarks, this also causes the proton to be positively charged and the neutron to be neutrally charged. However, quarks are not the only elementary particles present in the universe. Altogether, the quarks make up for about half of the elementary particles for mass, the fermions. The leptons fill the other half of the group. Together with the electron neutrino, the electron makes up the first generation of leptons. This does mean that there are in fact more generations of fermions. In total, there are 3 generations of fermions, shown in the table above. It shows that the muon is a second generation lepton, indicated with the greek letter μ (mu). This is due to the fact that it is an unstable particle, meaning that it will fall apart after a certain amount of time. Also, it is not a natural particle, in the sense that is does not appear in nature without having been in some sort of process, just like the element Technetium (Tc), which is a man-made element. Also, the higher the generation, the higher the mass of the particle. For example, the muon is roughly 200 times as heavy as the electron, weighing around 105.7 MeV/cm^3.

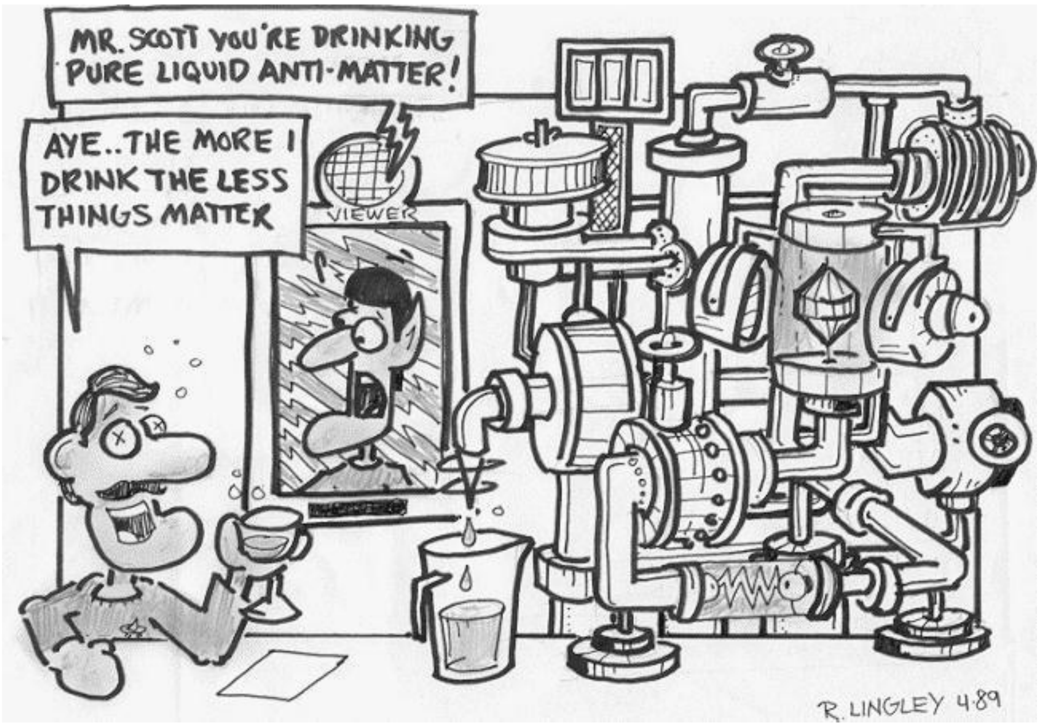
	Generation I	Generation II	Generation III
Quarks	Up-quark U +2/3 2.4 MeV/cm^3	Charm-quark C +2/3 1.27 GeV/cm^3	Top-quark T +2/3 171.2 GeV/cm^3
Quarks	Down-quark D -1/3 4.8 MeV/cm^3	Strange-quark S -1/3 104 MeV/cm^3	Bottom-quark B -1/3 4.2 GeV/cm^3
Leptons	Electro Neutrino ν_e 0 <2.2 eV/cm^3	Muon Neutrino ν_μ 0 <0.17 MeV/cm^3	Tau Neutrino ν_τ 0 <15.5 MeV/cm^3
Leptons	Electron e -1 0.511 MeV/cm^3	Muon μ -1 105.7 MeV/cm^3	Tau τ -1 1.777 GeV/cm^3

A table of all the fermions in the universe. It shows each fermion's name, identification letter, mass and electrical charge.

"Particles, particles, particles."

Paragraph 1.2: Anti-matter

While on the topic of particle physics, it is also worthy to note that all particles in the universe have their own anti-particle. During the creation of the universe, an equal amount of matter and anti-matter was made, although scientists do not know what happened to all the anti-matter, since they cannot find it. Anti-matter is basically the same as ordinary matter, the only difference is that the electrical charge and quantum spin are opposite of the ordinary matter's. For example, an anti-proton (or negatron, as it is less commonly called) would be written as p, with an electrical charge of –1 instead of +1. So far, scientists were able to detect natural anti-matter from beta-radiation and even produce anti-matter in laboratories. They have been able to produce an anti-hydrogen atom (H) with an anti-proton and a positron (an anti-electron). An interesting thing about an anti-particle is the property that it will annihilate both itself and the other particle if it touches an ordinary particle of the same type. For example, the result of an electron and a positron colliding would result in the annihilation of both of them and their energy-mass converted into heat and/or gamma-radiation. However, if a proton and an anti-proton would collide, the quarks could rearrange in such a way that pions (π) are created, which would fall apart into neutrinos, electrons and muons, or their anti-particles.



Chapter 2: A muon's life

Paragraph 2.1: The creation of a muon

Now we know what a muon is, let's take a look at how one is created. As told in paragraph 1.1, a muon cannot be found in nature, without going through a process of some sort. In order to create a muon, at least 105.7 MeV is needed, the energy of a muon. Note that this can only be center-of-moment (or COM) energy, which means it can only be achieved by letting two particles collide with a very high velocity. Even nuclear weapons do not have the energy needed to create muons. A good example of such collision is what researchers do at Cern in Switzerland. Two groups of particles, usually protons, are brought to a speed close to the speed of light (as close as they can get). Once both groups have attained enough velocity, the researchers let the groups collide. With this much energy, two colliding protons will instantly fuse, followed by nearly immediate decay, creating other particles that can be detected. This will not immediately produce muons, as it would violate the law of conservation of quantum numbers, but it will create pions, which will decay into muons. However, if muons do not naturally exist in nature, how have scientists been able to detect them? The answer lies about 50km above us, in the ozone layer. Cosmic rays, mainly protons, crash into the ozone layer at a speed close to the speed of light (a lot closer than the speed achieved in Cern). This again causes instant fusions and sends pions towards the earth. After several meters, these decay into muons and neutrinos, their favourite product, which are sent towards the earth.

Paragraph 2.2: The life of a muon

We know that muons are unstable and therefore will eventually decay into smaller particles. But exactly when and into what particles do muons decay? Let's first look at the lifetime of a muon. Scientists have established that a muon's lifetime is roughly 2.2 microseconds. Even if it is the 2^{nd} longest lifetime known amongst the unstable particles, it is still an increble short timespan. This also causes the next question to be asked: How can a muon still reach the earth in such a short timespan?
We know that muons move with a speed close to the speed of light, so for this calculation, let's just take c as the speed of a muon. The distance covered by the muon will than be:

2.2 μs * c =
2.2 μs * ~300,000,000 m/s =
2.2 s * 300 m/s = ~660 metres

So we now know that a muon can travel roughly 0,66 km before decaying. However, in the previous paragraph, we noted that muons are created at least 50 km above us. How is it possible for the muons to travel all the way from the ozone layer to earth without decaying? The answer to this was given by Einstein's theory of relativity. This particular case would be part of the 'Time dilation' effect. This part theorises that objects that travel with a big velocity move slower through time. This is also part of the twin paradox: If you had identical twins, let's say two boys, and one of them was to travel in space with a speed close to that of light, he would return to earth younger than his twin brother currently is. A weird thing about time dilation is that the object with the high velocity does feel the time passing as usual. Referring back to the two boys. Let's say the spaceship traveled for 10 years with a very high speed. The time dilation effect causes the traveling boy to be 3 years younger than the boy that stayed on earth. Now the thing is that for the boy in the spaceship, it felt like 7 years had passed, while in fact 10 years had passed. Back to the muon. We know that the muon has a lifespan of 2.2 μs. If we add the time dilation into the equation, we see that the muon can live a lot longer than those 2.2 microseconds. While 2.2 microseconds have passed for us, only a fraction of those 2.2 microseconds have passed for the muon, which means the muon can still live on. This happens to such an extent that the muon can live long enough to reach us on the surface of the earth.

Paragraph 2.3: The decay of a muon

We've heard that muons decay. But what does actually happen when a muon decays? Muons decay following the weak interaction, which is one of the 4 basic physical forces, alongside gravity, electromagnetism and the strong interaction. There are certain laws that have to be obeyed while the muon decays. The first one is, that whenever a lepton decays, a neutrino with the same name is to be created. In this case, a muonneutrino will be created. The second law is the law of conserving lepton numbers. This means that when you add the amount of leptons and subtract the amount of antileptons, you have to get the amount of leptons you started with. The third and last law is the law of conserving charge. Because the muon has a charge of –1, the only thing that can be created is an electron, because it is the only particle smaller than the muon with the same charge. This results in the following three particles:

- A muon neutrino
- An electron
- An electron antineutrino

Or, in a formula:

$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$

Now, if we check the charge and the lepton numbers:

Leptons:	1	=	1	– 1	+	1
Charge:	-1	=	0	+ 0	+	-1

Antimuons decay the same way, however, instead of the particles above, all their antiparticles are created: A muon antineutrino, a positron and an electron neutrino. Other particles may be created in the decay of the muon, however these have a net spin and charge of 0, for example an electron and a positron.

Chapter 3: Detecting muons

Paragraph 3.1: The muon detector – The muon lifetime experiment

We know what muons are and where they come from, but how do we detect them? Because of the small size of muons, they can practically go through anything. However, anything between the source of the muons and the detector will decrease the chance of the muon reaching the detector. The machine used to detect muons is just called a muon detector. It consists of a couple of parts. The most important part is an organic gel, which is put in the centre of the detector. This gel has a special property, namely that it sends off a flash of light every time a particle goes through it. This gel is connected to a small detector which detects these flashes, and sends an electric signal down the wire when it detects one. Of course, daylight or lamps would interfere with this. This is why the gel and the small detector are wrapped in straps of plastic. This all is put into a metal box with a glass lid, to make sure it doesn't get damaged or the plastic is pulled off. The electrical signals given off by the detector are translated into a graph. However, not all signals are that can be used. This is because we are looking for the decay of muons, not just all muons. Every time the detector detects a flash, it will start counting. If after a certain amount of time there is no other flash, it means the muon went straight through the machine. If there is a flash however, there are two possibilities: Either the muon decayed, causing the organic gel to flash again, or another muon entered the machine. In order to filter out the second possibility, the amount of time allowed is set to a very small number. Of course, sometimes there will be 2 muons that arrive at the same time, but this number is so small that it doesn’t matter in the long run.

Paragraph 3.2: The actual experiment

The University of Leiden has a couple of these muon detectors, one of them which I got to use. The machine was linked to a computer, which collected all the data in a special program. The program worked like this: Whenever the detector detected two hits with an inbetween time of < 2.5 microseconds, it notes the time of the hit and the time between the two muons. This will result in a huge list of these hits, which were turned into a graph in windows Excel. The expectations are that the graph is an e power function: $Y = Ae^{-Bt} + C$. The value that is of importance is B, as that is the expected lifetime of the muon. Of course, a function of that type will never go through all the points on the graph, so a line has to be drawn that the distance from all the points to the line is minimal. A technique called RMS, Root mean square, is used for this. Of course, to calculate everything would take ages, so Excel is used. It works like this: First, you take values which could be good values for the function. Then, you calculate d(p,Y) for all the points. After that, you take the absolute value of all the distances and add them. You'll get the following function:

$$D = d_1 + d_2 + d_3 + ... + d_n \text{ , In which } d_n \text{ is defined as } d_n = |d(p_n,Y)|.$$

Since the points p are set values, and the variables A, B and C have been chosen, a value for D will pop out. However, we want to make this experiment as precise as possible, random guessing isn't going to cut it. That why we'll make better guesses for the values of A and C. In order to find C, Ae^{-Bt} will have to reach zero:

$$\lim_{t \to \infty} Y = Ae^{-B*\infty} + C = 0 + C = C$$

We can now easily calculate the value of A, by taking B = 0 $e^{-Bt} = 1$:

$$Y(0) = Ae^{-B*0} + C = A*1 + C = A + C$$

Since we already know C, we now also know A.
For the last part, we can let Excel calculate B, as doing it by hand (or calculator even) will take a very long time (we've got the values for p already in Excel). To get the most precise answer, we'll have to let Excel do all the calculating for us; this is because the estimated values for C and A are probably not correct.

Paragraph 3.3: Excel: the calculations

All the hits were put in a .txt file and then imported to windows excel. The hitdata can be found in the attachment (lifetime_hitdat). In order to further process this data and do calculations with it, we'd have to make something called a histogram. The histogram can be found in the attachment, page 9. (due to the size of the documents, which would come down to about 65 pages, it's just digital attachments) Now, instead of calculating the values of A, B and C by ourselves, we let excel do the work for us; we did estimate the values though:

C = 3

A = 34

B = 0,0005

While A and C can be estimated with quite some accuracy, B is a bit harder to estimate. However, these are just the values excel starts calculating at, which means it will find the correct answer anyway, even if you add a rediculously high value for B (it will take a lot longer or even crash though).

Now if we take a look at column C, I've added a formula there:

=$I$1*EXP(-$I$2*A2)+$I$3

Which is really just the same one as the standard formula for an e power function

$=A*e^{-B*A2} + C$

Because we have put A in I1, B in I2 and C in I3. Note that A2 is the cell, not another value for A. In column C, we now see the amount of hits that 'should have' taken place, according to the formula we just put in. Now, in the next column, we add

=(B2-C2)^2

This is the difference from the mean ($Ae^{-Bt}+C$) squared. Now we add it all up (37329,37 in cell I4) and we take the mean of that:

I4/I5, in which I5 is the amount of cells that D spans

Now we take the square root of this and we got 3,027 as a result. This is the RMS of our graph, which means we got pretty close by (0 would be the graph). Now, we want to make our RMS as small as possible, to get the best graph possible. We used excel solver to get the values we want:

A = 336,52616

B = 0.000582

C = 2.807567

Paragraph 3.4: Calculations with the results

After the calculations done with Excel, we got the results for A,B and C. But first, we'll need another value, the half-life time. The half-life time is the amount of time that has to pass in order for half of the particles to have decayed, noted as $t_{1/2}$. We can easily read this in our graph, which got us $t_{1/2}$ = 1462.5 ns.
We'll now calculate the time dilation. The following formula takes effect:

$$\Delta t' = \frac{\Delta t}{\sqrt{1-v^2/c^2}}$$

In which
$\Delta t'$ is the time dilation effect
Δt is the lifetime (or mean lifetime)

To get the lifetime, we can do two things:

1) $t_{1/2}$ * 1/ln(2)
2) λ^{-1}, λ is in this case the decay rate, not the wave length (which also uses a lambda). We determined this as the slope of the graph, B.

The first method would give us 2109.94ns as an answer, the second method gives us 1717.327ns as an answer. These difference between might seem big, but such are the measurement inaccuracies. Now the only thing left for us to get is the speed of the muons. If we just inserted the ordinary s/t, we'd get a value > c, resulting in a negative value under the root sign. So, we need to get the speed in another way. A research[1] has shown that the avarage speed of a muon is 29.8 ± 2.5 cm/ns, which is 99,4% of the speed of light. In other words, small enough for our calcuation.

$$\Delta t' = \frac{\Delta t}{\sqrt{1-0.994^2/c^2}} = \frac{\Delta t}{\sqrt{0.01196}} = 9.14\ \Delta t$$

Which means that the time dilation effect is about 9.14.
Now, we should get a reasonable amount of muons that is capable of reaching the earth's surface:

$15*10^3$m/0.994c = 50.3 μs
50.3 μs/(2.11*9.14) = 2.61 lifetimes   50.3 μs/(1.72*9.14)
1/(e^2.61) = 0.074 = 7.4%   1/(e^1.72*9.14) = 0.020 = 2.0%

Because the 2.11 is closer to the actual lifetime of muons, the 7.4% is more accurate.

1 http://web.mit.edu/lululiu/Public/pixx/not-pixx/muons.pdf

Chapter 4: A use for muons

Paragraph 4.1: Nuclear fusion

With the growing need of energy and the sources of oil and coal being depleted far too quickly, nuclear fusion is seen as one of the few options. However, the current process of nuclear fusion is extremely dangerous as you'd require a extremely high temperature (known as thermonuclear fusion) or it is highly inefficient (beamnuclear fusion). Scientists have been experimenting and have found a new method of nuclear fusion: Muon-catalysed nuclear fusion. It is a process that can happen in room temperature. Due to muon being about 207 times as heavy as an electron, the two atoms to be fused are brought together 207 times as close. Being this close, the chance of a fusion is greatly increased. The most common muon-catalysed nuclear fusion is the deuterium-tritium (or dt) fusion. It requires just a muon, a deuterium atom (^2H or D) and a tritium atom (^3H or T). The muon either starts as a free muon, attracting both atoms, or starts instead of the electron in either of the atoms. Both ways will finally result in a $(d\text{-}\mu\text{-}t)^+$-ion. The deuteron and the triton (the nuclei) interact, creating a particle that immediately decays into an α–particle and a neutron, releasing big amounts of energy. The muon remains unharmed (usually, sometimes it sticks to the α–particle) and thus can start another reaction. The reaction takes place in less than a picosecond 10^{-12}, the most of the time the muon spends looking for a new pair of atoms. This could be a good source of energy, if not for 2 things: First of all, the muon can stick to the α–particle, meaning it can only trigger a couple of hundred reactions, second of all, creating a muon is very expensive, the expense being bigger than the outcome. In order to make muon-catalysed nuclear fusion profitable, the expenses of the muon need to be cut down.