The Theory of Relativity

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Introduction

In this TraPe, I will introduce you to Einstein and explain parts of the theory of relativity, such as Einstein's formula; $E=mc^2$, the concept of space-time and time dilation. I will also show you how this theory has been proven.

I was inspired by a movie called "Interstellar". I watched it in the beginning of summer last year. After seeing it, I felt the urge to do researches about gravity and black holes. These researches took me to the theory of relativity, which I then decided to try to understand.

There are two theories of relativity: the special and the general. Albert Einstein (1879 – 1955) published the theory of special relativity the 26 September 1905. The theory of general relativity then followed in 1915. The main difference between the two is that special relativity doesn't include acceleration or gravity, which is why we need general relativity.

Einstein

Born the 14 March 1879, Albert Einstein was a German theoretical physicist. Although he was a Jew, Einstein went to a catholic elementary school and later transferred to a gymnasium where they had and advanced level of primary school and had secondary school education too. Having a bright mind and a natural talent for mathematics and physics, Einstein had taught himself algebra and Euclidean geometry by the age of twelve. At that age, he received a family tutor, but Einstein was too quick even for the tutor. However advanced he was in maths, he certainly didn't excel in respecting authority and the school's teaching methods. He later on described the spirit of learning to have been lost in too strict rote learning.

By the age of fourteen, Albert had taught himself calculus and at the age of fifteen he left for Pavia (Italy), to rejoin his family who had left for business reasons. During his stay in Italy, he wrote an essay titled "On the investigation of the state of the ether in a magnetic field". His love and interest in algebra and geometry was so strong that it convinced him the world could be understood as a mathematical structure.

At the age of thirteen, Einstein discovered the violin, which he taught himself and never stopped playing. Music had a great impact on his life, he even later stated that: "If [he] were not a physicist, [he] would probably be a musician. [Einstein] often think[s] in music. [He] live[s] [his] daydreams in music. [He] see[s] [his] life in terms of music... [He] get[s] most joy in life out of music."

When 16, Einstein tried entering the Swiss Federal Polytechnic (in Zürich) but failed in all subjects, except maths and physics, where he had extraordinary grades. He was sent to the Argovian cantonal school, still in Switzerland, and completed his secondary school. While staying with the Winterlers, a professor's family, he fell in love with Marie Winterler.

To avoid military service, Einstein renounced his citizenship in Germany. At seventeen, he applied for a four-year mathematics and physics teaching diploma program. There, he met Mileva Marić with whom he became great friends. That friendship turned into romance. They had a daughter in 1902, but she died or got put up for adoption a year later. (Historians aren't sure.) Einstein got his Federal Polytechnic teaching diploma in 1900.

In 1903, Einstein and Marić married and had a son in 1904. 1905 was the year Einstein wrote his "Annus Mirabilis" papers. Marić and Einstein had another child in 1910, called Eduard.

Albert became a professor at the German Charles-Ferdinand University (in Prague) in 1911. In 1912, he returned to Zürich and got a job as a professor of theoretical physics. He taught analytical mechanics and thermodynamics until 1914. That year, he moved to Berlin where he was voted for membership in the Prussian Academy of Science.

The Nobel Prize in Physics was attributed to him in 1922 for "his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect". Until 1924, the general theory of relativity wasn't accepted all over the globe. It was rather seen as "controversial".

Einstein and Marić divorced in 1919 due to Einstein's love for his cousin Elsa Löwenthal, which he married the same year. Together, they moved to the United States in 1933, fleeing Nazi Germany who wanted Einstein dead, and his works burned.

In 1939, Einstein was encouraged by a physicist to make President aware of the German's knowledge about the atomic bomb, and their will to build one. Together with two other refugees, they wrote a letter to the president, asking to put his attention and financial support in the fabrication of an atomic bomb. Einstein revealed in 1954, that this was, in his eyes, his biggest mistake; singing that letter.

On 18 April 1955, Einstein died due to an internal bleeding in the region of the abdomen. Before his death, he was offered surgery, but he refused. He stated: "I want to go when I want. It is tasteless to prolong life artificially. I have done my share; it is time to go. I will do it elegantly." I personally find these very courageous and wise words, knowing the importance he had to the people, which he knew about. Einstein was writing on a speech when he got taken to the hospital and he continued working until he drew his last breath. (Which I also find very inspiring; the fact that he didn't consider death as a special event to be prepared for, rather a part of life, or its end, which would simply happen.)

$E=mc^2$

This equation is probably the most known part of Einstein's theory of relativity, but I doubt that everybody who's heard of it knows what it means. In the following pages I will explain what the letters stand for, what energy, mass and the speed of light are, and I'll explain the meaning of the equation. But first let me quickly introduce you to it.

Einstein originally formulated his thought as $m=E/c^2$, but it was later rewritten as $E=mc^2$. The formula is believed to have been derived by an Italian industrialist named Olinto De Pretto who published it two years before it was mentioned in Einstein's work, but as this has never been proven, it is often seen as unimportant or irrelevant.

The most important thing is to remember the name of Albert Einstein, who published the formula in his last article about the theory of special relativity in *Annalen der Physik*, in 1905. Now, to understand what it means, I invite you to read the next few pages.

Energy (E)

Energy is the ability to perform work, such as creating movement, releasing warmth or change the state of a substance. It can also create particles in empty space.

The amount of energy inside of a closed system can’t increase or decrease.

Types of energy	**Definition**
Thermal energy	Thermal energy could simply be translated to heat. It is the energy produced by the movement of particles within a system.
Kinetic energy	Kinetic energy is motion. It ranges from 0 to a positive value.
Potential energy	Potential energy is the energy of an object’s position.
Mechanical energy	Mechanical energy is the sum of kinetic and potential energy. It results from movement or the location of an object.
Electromagnetic energy	Electromagnetic energy is the energy portrayed by light of electromagnetic waves.
Nuclear energy	Nuclear energy results from nuclear reactions.
Chemical energy	Chemical energy is caused by chemical reactions between atoms or molecules. There are different forms of chemical energy.
Gravitational energy	Gravitational energy is the attraction between two objects based on their mass. It can be a basis of mechanical energy, such as the kinetic energy of a planet orbiting around the sun or the potential energy of a book placed on a table.
Sonic energy	Sonic energy is sound. So it is caused by soundwaves.
Ionization energy	Ionization energy binds electrons to a nucleus.

Mass (m)

Mass is the quantity of matter an object has. Matter is defined by something that takes up space. Anything you can see touch, or move by applying a force is matter.

We distinguish between two different masses: gravitational and inertial mass. Although both are equivalent, they are measured differently. Gravitational mass is measured by the impact of gravity on a body, while inertial mass is determined by the acceleration of a body when it is exposed to a force that is not due to gravity.

To calculate gravitational mass, we use $Fg = (Gm_1m_2)/d^2$. Here Fg is the force due to gravity, *G* the universal gravitation constant, m_1 the mass of the first object, m_2 the mass of the second object and d the distance between the centers of both objects.

To calculate inertial mass, the formula $m=F/a$ is used, where m stands for mass (in kilograms), F is force measured in newtons and a is the acceleration. This also means that F and a are constant; if F increases, so does a.

The difference between mass and weight

Weight is the force gravity exerts on an object. It varies from place to place, an object doesn't weigh as much on the moon as on earth, because the pull of gravity is smaller. Mass, on the other hand, is independent on gravity. A given object has the same mass on earth than on the moon.

Weight
Weight= **m**ass x **g**ravity

Mass
mass= **d**ensity x **v**olume

Weight is measured in newtons, whereas mass is measured in kilograms.

Speed of light (c)

The speed of light, as the name already indicates, is the speed at which light travels. Though one precision has to be made: it is the speed at which it travels in vacuum. Which, in numbers, comes down to 3.000.000 m/s (299.792.458 m/s).

Could we (as humans) travel at the speed of light?

No, it is impossible for any particles with a mass to travel at the speed of light. As Roger Rassool (a physicist) once said, “as object’s travel faster and faster, they get heavier and heavier – the heavier they get, the harder it is to achieve acceleration, so you never get to the speed of light.” This has been proved by Bertozzi, a physics professor.

His experiment consisted in getting electrons to move at the speed of light. To achieve this, he used the same amount of negative energy as the electron, so as to push them away. To increase the speed of the electron, he increased the amount of energy.

After a while, Bertozzi realised that he had to add a lot more energy to get a constantly decreasing repulsion. In fact, every repulsion was half as fast as the one before. To make this a little clearer, here is an example:

You want to go from your house to your girlfriend’s. Every step you make, is half as big as the one you just took. Your house being point A, your girlfriend’s point B and c, d, e, f are the different steps you make, this is what your course looks like:

You will notice as you move forward, that you can never possibly reach point B. And this is exactly what Bertozzi discovered. As close as we can get to the speed of light, we shall never reach it.

Then how come photons* can?

*photons are the particles of which light is made

After all, photons are particles just like electrons, right? Wrong. The reason photons can travel at speed of light is because they don’t have a mass. Light is actually pure energy, meaning photons are too because light and photons are the same. Photons have the ability to behave like particles but also like waves, which makes it possible for them not to have a mass and therefore to travel at the speed of light.

Why does the speed of light have to be squared?

To be honest, I do not understand this. To make sure I don't say anything wrong, here is word for word an explanation of NOVA:

"It has to do with the nature of energy. When something is moving four times as fast as something else, it doesn't have four times the energy but rather 16 times the energy—in other words, that figure is squared. So the speed of light squared is the conversion factor that decides just how much energy lies within a walnut or any other chunk of matter. And because the speed of light squared is a huge number—90,000,000,000 $(km/sec)^2$—the amount of energy bound up into even the smallest mass is truly mind-boggling."

The equation

When Einstein "created" his formula, he took the speed of light into consideration to calculate the mass of an object. The equation says that energy and mass are connected, like two faces of the same coin, and thus interchangeable.

The equation is used for various situations in our daily lives. For example, radioactivity, that needs $E=mc^2$, is used for X-ray scans, MRI scans, or even radiotherapy for cancer patients.

Solving the equation

Let's calculate the energy an average adult man in Europe contains. First, collect the information we need.

E= x (measured in joules)

m= the average weight of an adult man in Europe is about 70kg

$c^2 = (3\times10^8 \text{ m/s})^2$

Now we can calculate.

$E = mc^2$

$E = 70\text{kg} \times (3\times10^8 \text{ m/s})^2$

E= 6 300 000 000 000 000 000 joules

An average adult man contains $6{,}3\times10^{18}$ joules of energy that is an awful lot!

Another example, with a paperclip. If we were to turn a paperclip into energy (using Einstein's formula to calculate it), that would make 18 kilotons of TNT. To give you an image, that's more or less the size of the bomb that destroyed Hiroshima in 1945. Of course, it is impossible for us to turn that paperclip into energy, because we would need temperatures and pressures higher than the ones at the core of our sun.

Space-time & time dilation

The first person to speak of space-time, was Hermann Minkowski. He came up with the concept as a way of interpreting the theory of special relativity. In Albert Einstein's general theory of relativity, he mentions space-time again. This time however, he comes up with his own idea of space-time, based on Minkowski's concept, but Einstein decides to make it curved, instead of flat.

Time dilation showed up in Einstein's work about special relativity. It is the difference between two observations of the time passing by, when one of them has been affected by an acceleration or gravity.

Space-time

Space

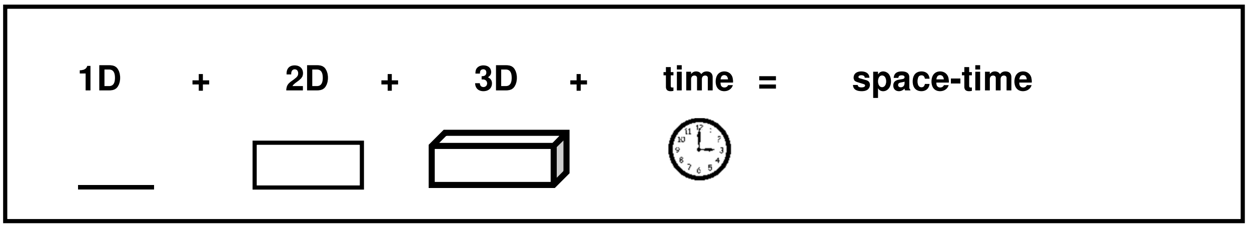
Space is composed of three dimensions; left/right, up/down, forward/backward.

Time

Time is a dimension for itself; the fourth. It cannot exist without movement, and movement doesn't exist without time. Time is used to measure events, but events require four dimensions to be measured. That is why time and space cannot be separated. They create a continuum called space-time.

Space-time

Space-time is a mathematical model that helps us understand how systems with extreme sizes, such as atoms or galaxies, work. It is, as already mentioned, the fusion of the three spatial dimensions and the dimension of time.



Special relativity dictates that space-time doesn't need a universal time component. This means that, events observed by people in motion will be seen in relation to where they are standing and/or how fast they are traveling, rather than in relation to a universal unit.

[Example with the cat. And that would already be an example for time dilation.]

Time dilation

To understand time dilation, there are many concepts you have to understand first. Starting with motion, we'll slowly work our way up to things such as frames of reference or length contraction, to arrive to our goal: understanding time dilation.

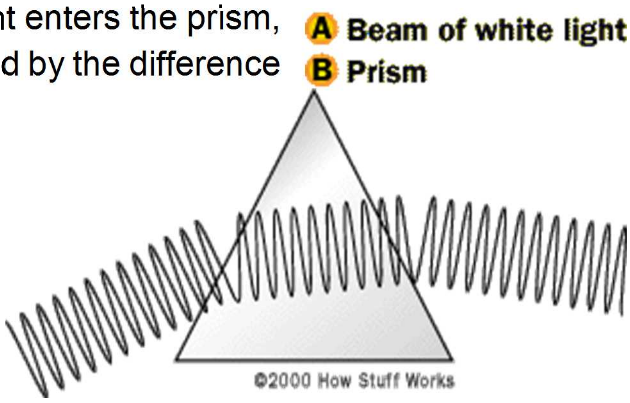
Motion is defined by the act of something changing its location in space.

Light, which is a form of energy, behaves in two different ways: it can act like particles or like waves. This is known as duality, meaning that light can act as a particle or as a wave at the same time. Light in its particle form is known as a photon. A photon is created by the release of energy of an atom when its electron orbiting close to its nucleus jumps to an orbital further away from the nucleus. The wave form of light has no specific name, it is simply a form of energy which is created by an oscillating (to oscillate means to change position in a regular manner about the central point) charge.

When light travels through space, it often faces matter in one form or another. When it travels from one medium to another, light bends; it is called refraction. (A medium is a substance, such as air or water, through which a force acts or an effect is produced.) The bending of the light, or even the blocking of certain of its frequencies, allows us to see separate colours.

For example, a rainbow can be seen when the sun's light is separated by the rain, or simply moisture in the air. The moisture bends the light and thus splits its frequencies which allows us to see different colours.

A prism can have a similar effect. When light enters the prism, the light bends down. This bending is caused by the difference of speed of the light. Light travels faster through the air than it does through the prism. So, when the lower part of the wave (we're talking about the light's wave) enters the prism, it slows down. Because the upper portion, that is still in the air, travels faster than the lower one, the wave bends.



It's a little like a skateboard rider. Imagine him going down the driveway and turning into the grass. His body will automatically lunge forward and fly off the board (that is, if he was travelling fast enough to start with). This is the same situation as the light bending, as it goes through different mediums. The skateboard and the person riding it were travelling at the same speed until the wheels hit the grass. All of a sudden, the skateboard is travelling much slower, if at all, so the rider bends forward. The rider is trying to continue travelling at the same speed he was before the wheels hit the grass.

Frames of reference are practically the base of the theory of special relativity, but what are they? A reference of frame is “where an observer happens to be standing”.

For example, you, at this very moment, are probably sitting at your desk, that is your reference frame. You feel like you are stationary (standing still), even though you know that, because you are standing on the earth, and the earth not only is revolving on its axis but is also orbiting around the sun, you are moving too.

A very important thing to remember is that, there is no such thing as an absolute frame of reference in our universe. Now what on earth does that mean?! Or should I say, what in this universe does that mean?? This statement basically says that, there is no place in this universe that is completely and entirely stationary. It declares that, since everything is moving, all motion has to be relative.

Let’s come back to you and your reference frame. We can both agree that the earth is moving, and because of that, even though you might be standing still, you are moving, too. You are moving through both time and space at all times, because no place’s or object’s location is unvarying. Meaning, there isn’t a single place or object on which to base all other motion; motion is relative.

Length contraction can be measured with the Lorentz Transformations. Lorentz Transformations are “mathematical equations that allow us to transform from one coordinate system to another*”. The quantity of contraction depends on how fast an object travels with respect to the observer.

Imagine you and your friend looking at a 30 cm long football. Now, your friends kicks the ball so it flies past you at 60% the speed of light. You, due to length contraction, would see the ball as a 24 cm long football. So, if the ball travels at 60% of the speed of light, you measure only 80% of its original length.

Keep in mind that all measurements are in the direction of the motion – The ball’s length doesn’t change because of its velocity, it only changes to you, thus in your frame of reference.

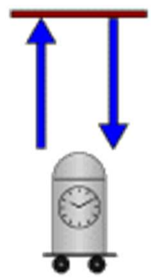
If you were running next to the football at the exact same speed, 60% the speed of light, you would measure its diameter to be 30 cm long. This situation is the same as you standing still next to the ball standing still.

Also, if you are holding a ruler and your friend runs at 60% the speed of light (let's pretend it's possible) with the ball, he would measure you and the ruler you're holding to be length contracted. He has equal right to view you as being in motion with respect to him.

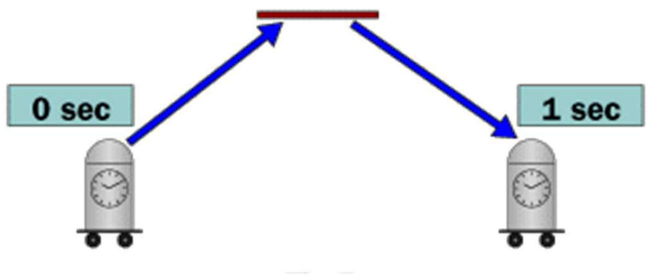
Now, we're nearing the explanation of time dilation, but first let's quickly see **the effect motion has on time**, before we jump to the big thing. As already mentioned, time changes with different frames of reference. This is called time dilation. Time is slowed down by motion, but it can only be taken into account at speeds close the speed of light. If the speed reaches that of light, time decelerates so much it actually stops. Of course, this is all theoretical, because nothing, apart from light, has ever been able to travel at the speed of light, as we saw earlier on ($E=mc^2$, speed of light). Please note that only an observer not moving with the time that is measured would notice.

To get a picture of time dilation, I'll use some examples.

1. Suppose we've got a light clock on wheels. A light clock is able to measure time by sending a beam of light from its bottom plate to its top plate. There, the beam is reflected back to the bottom plate. Since the speed of light is constant, the time the clock measures must be constant too, regardless of motion. Now, we look at the light clock and see that it takes 1 sec for the beam of light to go from the bottom plate to the top plate, and then back again.



   Let's say we push the clock so it rolls to the right, while we remain standing still. In the first example (light clock standing still), the light beam would travel vertically from one plate to another. In the second example (light clock rolling to the right), the light's path changes to a diagonally up and down travel. So what does that mean?



   We know that the clock that's standing still needs 1 sec to send a light beam from bottom plate to top plate to bottom plate. We also know the speed of light to be constant. Thus, the beam has the exact same speed in example one and in example two, no matter where we are standing. But in example number two, it looks like the light travels further, because it travels at angles, and it does. It takes the light beam longer to do the bottom-top-bottom way in example two than it takes the light in example number one. But the speed of light hasn't changed.

Now we've added up all these informations, let's see what they tell us. If the speed remains unchanged and the distance increases, that can only mean that the time has to increase too. (Because speed is distance divided by time.)

Suppose the clock in example number two is rolling to the right at a speed of 90% the speed of light. Since you are standing still, you would measure the time the light beam takes to do a full bottom-top-bottom cycle to be 2,29 seconds, instead of only 1. Please note that anyone who would run or fly (or be in motion in any way) with the clock would measure a full cycle to take 1 second, because the clock wouldn't be moving in respect to them.

2. In this example, I'll use twins to illustrate time dilation. Imagine there is a pair of twins born on earth. At some point in life, one of them decides to take a ride in space, travelling near the speed of light (at exactly 90% of the speed of light). 57 years later, he comes back to earth to find his brother, who is suddenly a lot older than he is.

   That is because brother A (the one who went to space) left for 57 years, but because he was flying at 90% the speed of light, he only experienced 25 years going by, while brother B (the one who remained on earth) waited 57 years on earth for his brother to come back.
3. The last example is the one that is the most often brought into play, and was used to prove Einstein's theory. Two atomic clocks were synchronized. One of them was taken on a high-speed trip on an airplane. When it returned, the clock that was on the plane was slower by exactly the amount the theory/equation predicted.

So, after all these explanations and examples, you probably ask yourself; what exactly is time dilation? The answer is pretty simple. It's the difference between two elapsed times. In the examples we saw, there were always two frames of reference, two different observations of the same action. The difference between the results of these observations is what is called time dilation.

The Proof

To understand a theory it is not only essential to read explanations, but also to see how it is present in everyday life. I will therefore explain, step by step, how I have measured the distance a muon can cover using the regular formula (d=tv) and Einstein's ($E=mc^2$).

What is a muon?

The muon is an elementary particle, classified as lepton, much like the electron, except it has a much bigger mass ($106MeV/c^2$). It has an electric charge of -1e. Muons are created by collisions of cosmic rays with particles in the atmosphere and have a lifespan of 2,2µs. The most interesting part about a muon, is that it travels at 98% speed of light.

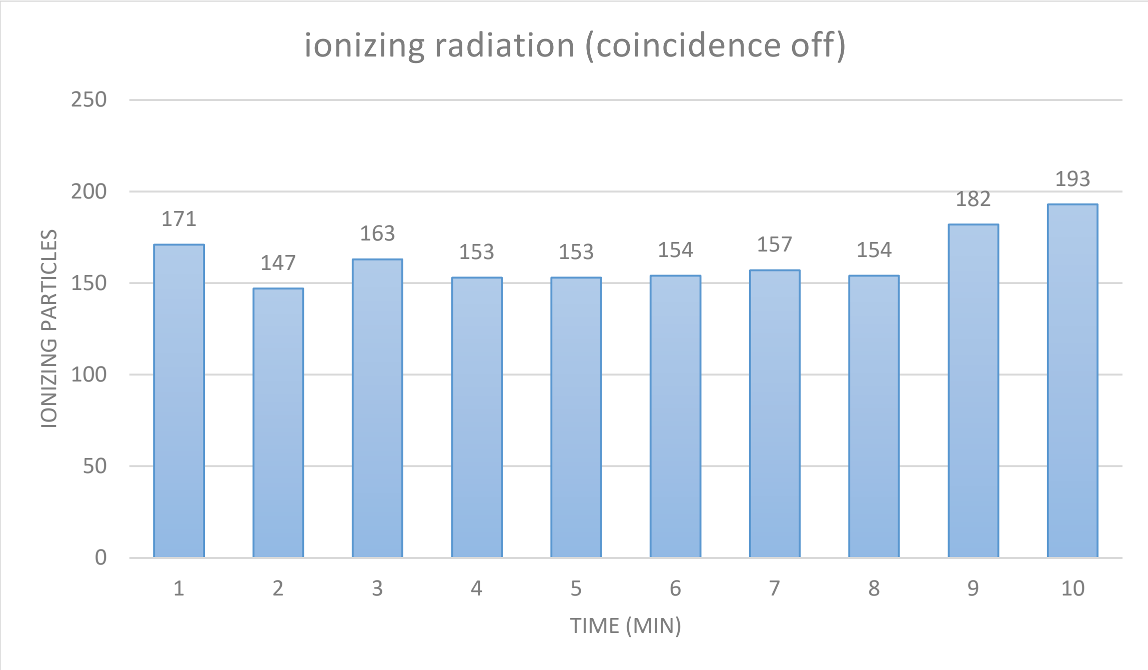
How do we detect muons?

As muons are very small, one can't see it with the naked eye. To detect these particles, I used a cosmic rays detector; an AMD13. The AMD13 is a model based on the AMD5 the Italian ADA project designed, with different measures (designed on the request of my school). It is composed of two superimposed cylindrical Geiger-Müller counter tubes with a length of 22 cm and a width of 2 cm (to shorten you can say GMT; Geiger-Müller tube) of the SBM 20 model. This model, which is one of the few to have electronic features, was produced in large quantities in the Soviet Union around 1980/1990 and works with a mixture of neon, argon and bromine.

Because muons arise from a collision of high energy, they have greater energies than the energy of radioactivity and are thus the only particles that are able to pass both Geiger-Müller tubes nearly at the same time. The detector has a coincidence switch. When turned off, the machine counts every particle that trespasses the GMTs, but when turned on, it only counts the ones that cross both GMTs nearly simultaneously.

My experience

For my experience, I used the schools AMD13 and let it measure the muons passing for 10 minutes with the coincidence off. I then turned it on. Here are the results:


ionizing radiation (coincidence off)
IONIZING PARTICLES
TIME (MIN)
250
200
150
100
50
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171
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163
153
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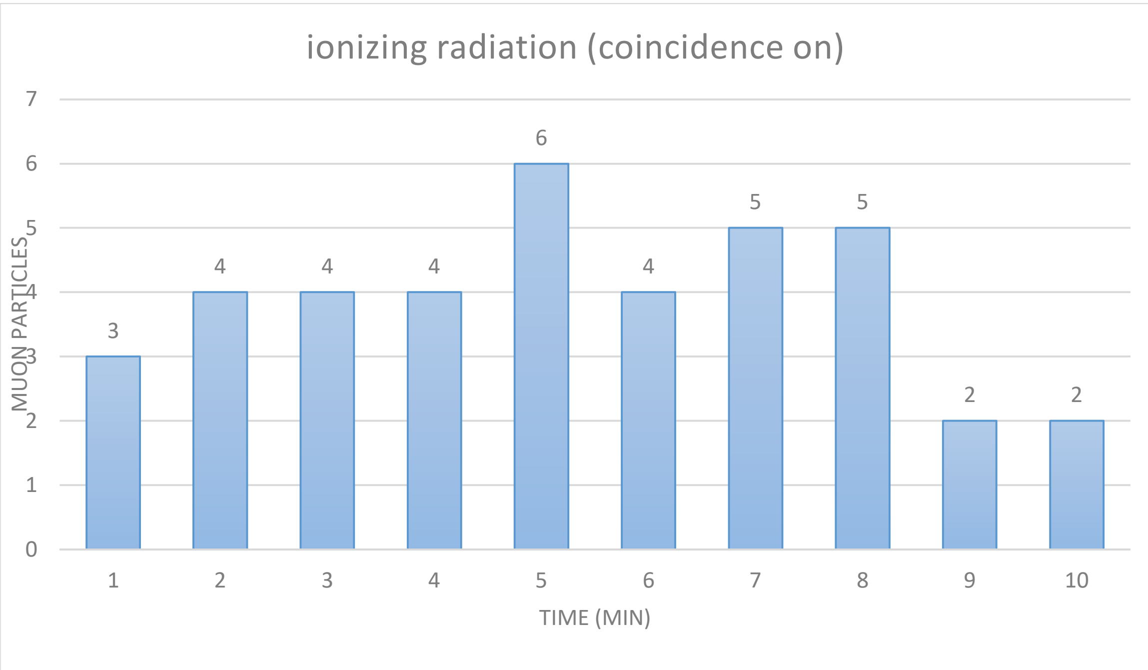
1 2 3 4 5 6 7 8 9 10


ionizing radiation (coincidence on)
MUON PARTICLES
TIME (MIN)
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Now, we know muons live for 2,2μs and that they fall from a height of 10km-15km. But, strangely, we are able to detect more or less 4 muons per minute on the surface of earth. The obvious question is: how?

If I calculate the distance a muon could cover within 2,2μs at 98% the speed of light using the regular formula, I obtain:

98% speed of light= 294 000 000 m/s

$$\mathrm{d} = \mathrm{tv} = 0{,}0000022s \times 294000000\mathrm{m}/s = 646{,}8\mathrm{m}$$

This answer must be wrong, as I was able to measure muons 10km away from the spot they were created. Instead, I'll use Einstein's formula, which will get me:

E= ɣ E_0

β= $\frac{v}{c}$

$ɣ^{-2}$= 1- $β^2$ so: ɣ= $\frac{1}{\sqrt{1-β^2}}$

ɣ (gamma):	Factor by which time, length, relativistic mass change for an object while it is in motion

Time dilation is measured by:

Δt= ɣ×$Δt_0$

Length contraction is measured by:

L= $\frac{L_0}{ɣ}$

In the case of muons:

$$ɣ = \frac{E}{E_0} = \frac{4GeV}{106MeV} = \frac{4000}{106} \approx 38$$

So:

$$β = \frac{v}{c} = \sqrt{1 - ɣ^{-2}} = \sqrt{1 - \left(\frac{E_0}{E}\right)^2} = \sqrt{1 - (\frac{106}{106\times38})^2} = 0{,}99965$$

Their lifespan in relativity:

$$\tau = ɣ \times \tau_0 = \frac{4000}{106} \times 2{,}2\mu s \approx 83\mu s$$

The distance they cover:

$$l = v\tau = \beta c\tau = \sqrt{1 - ɣ^{-2}} \times cɣ\tau_0 = \sqrt{ɣ^2 - 1} \times c\tau_0 = \sqrt{\left(\frac{E}{E_0}\right)^2 - 1} \times c\tau_0$$

$$l = \sqrt{\left(\frac{4000}{106}\right)^2 - 1} \times 299\,792458 m/s \times 0{,}0000022 s \approx 24\,879{,}69 m \approx 25\ km$$

This answer is a lot more reasonable, considering the fact that some muons are capable of reaching the depths of some mines.

Conclusion

As I said in my introduction, I was driven towards this subject by the movie "Interstellar", which I totally recommend watching. I didn't think it would be as much work as it turned out to be, because finding informations is pretty easy. The most difficult part is understanding what all these informations mean, and being able to reformulate them in a way that isn't too complicated, but still doesn't leave out too many details.

I am glad that I pushed myself to finish this TraPe, because I felt like giving up many times, but my passion and curiosity for this subject were too strong. I think it's a work to be proud of.

Also, I wouldn't have gotten here without the help of many people, including my science teacher, Mr. Grana, who assisted me and helped me find the most important informations and structure my work. In other words: Thank you.

To make sure I pass on my interest in this subject, I remind you that this doesn't sum up Einstein's entire work about relativity, nor does it include anyone else's. Therefore, I invite you to browse the internet or spend hours in the library to find out more about this fascinating subject, that is part of our daily lives.

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