

Aspects of the Year of Einstein 2005

Muons, Coincidences and Time Dilation

Alan C Pickwick

Manchester Grammar School

Synopsis

- Simple explanation of Time Dilation.
- Illustrate Time Dilation using Cosmic Ray Muons.
- Describe Cosmic Rays and Muons.
- Demonstrate a Classroom Experiment.

The Beginning

The Theory

- Einstein (1905) published paper on Special Relativity. Predicted that time is affected by the motion of the observer, relative to the event.

Experimental Proof

- Ives & Stilwell (1938) – Changes in the spectra of moving atoms – not the Doppler Effect.
- Rossi & Hall (1941) – Cosmic Ray Muons detected at the surface of the Earth.

Time Dilation

- In our daily lives we perceive time as a steady flow and the same in all places.
- However, if clocks move relative to us, time does not behave so simply.
- The theory of special relativity is needed to explain what we observe.

The Problem

- Just let me get this right. You say:

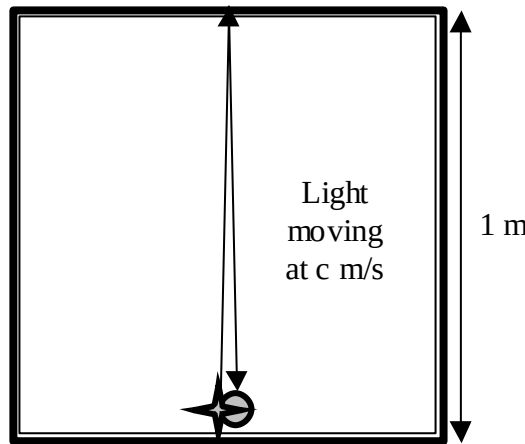
‘Moving clocks run slow?’

I don't believe it !!

- It's my job to convince you of this.
- So how do we measure time?

Investigate a Stationary Clock

- Send a flash of light from one side of a box to the other.
- Reflect it back to its starting point.
- This is the basic unit of time for our experiment.



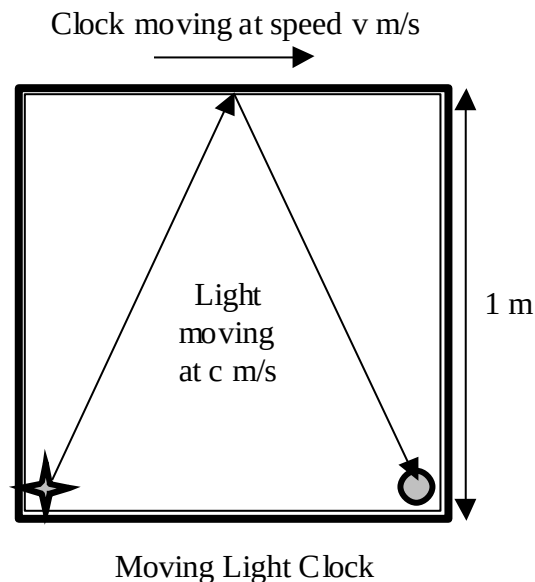
Stationary Light Clock

Key Point

- We stand still next to the box.
We do not move *relative* to the box.
- This means that we measure the
‘Proper Time’ for this event.

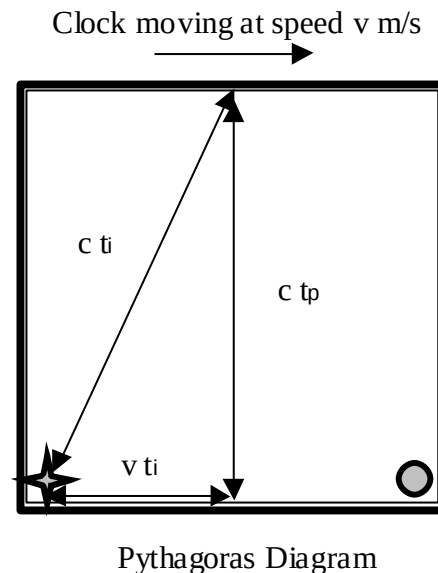
Investigate a Moving Clock

- Watch the same experiment but as the box moves past us.
- The flash of light seems to take a diagonal path across the box. It seems to take longer to complete its journey.



Investigate a Moving Clock

- Use Pythagoras's Theorem:
- $c^2 t_i^2 = c^2 t_p^2 + v^2 t_i^2$
- Rearrange and take the square root of both sides:
- $t_i = t_p / (1 - v^2 / c^2)^{1/2}$
- When there is relative motion, the denominator is less than unity, so the Improper Time (t_i) is always greater than the Proper Time (t_p).



Investigate a Moving Clock

- Consider a clock passing at 50 m/s:
- $t_i = t_p / (1 - (50)^2 / (300\,000\,000)^2)^{1/2}$
- This change is so small that it cannot be evaluated directly with a pocket calculator!
- The Improper Time (t_i) is about 1 part in 72 000 000 000 000 greater than the Proper Time (t_p).

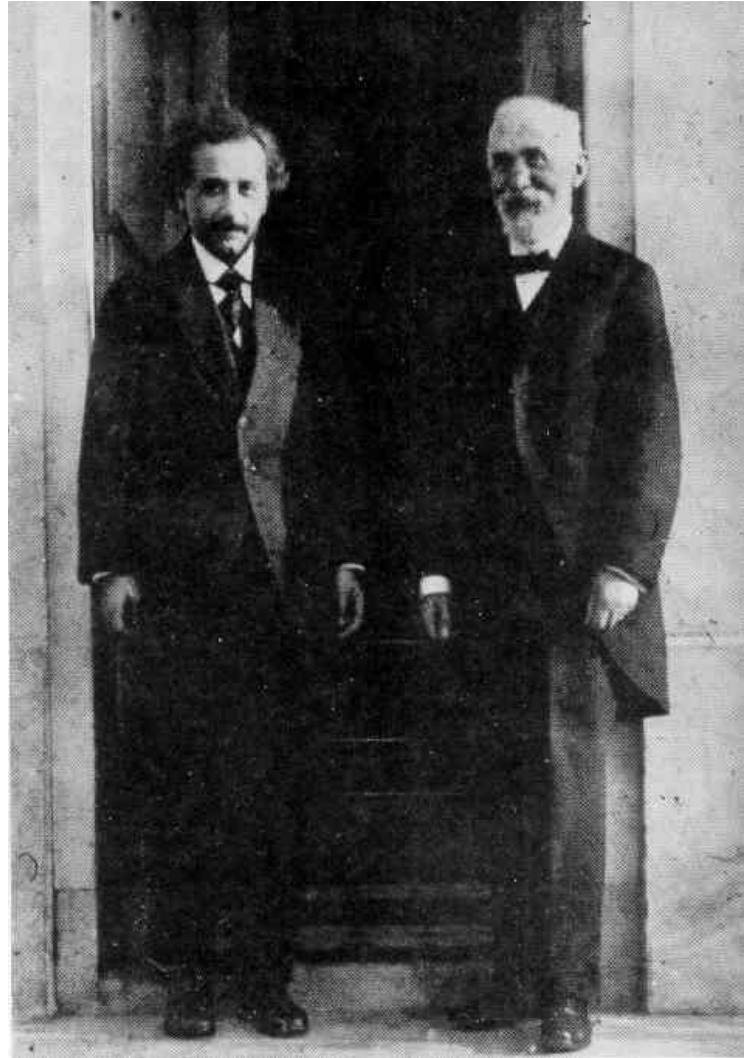
Clock Summary

- This demonstrates that the clock *moving relative to us* runs more slowly than the stationary one.
- This effect is very small at normal speeds.
- If a clock passes at a speed of 50 m/s the difference is about one part in 72 million million parts.

Historical Perspective

- Lorentz (1853 -1928) had already established the theory for transforming motion from one moving frame to another before Einstein's 1905 paper on Special Relativity.

(Rijksmuseum, Leiden. Circa 1920)



How to Demonstrate the Effect?

- To be able to measure Time Dilation, we need to observe some particles that are travelling very quickly.
- We will choose Muons that are created by Cosmic Rays.
- So what are Cosmic Rays and Muons?

What are Cosmic Rays?

- Cosmic rays are very fast protons and light nuclei.
- They arrive from the Sun and from the Galaxy (probably from supernova explosions).
- Cosmic rays collide with nitrogen and oxygen nuclei in the top of the atmosphere, about 60 km above the surface of the Earth.
- Collisions produce many sub-nuclear fragments that travel down towards the surface.
- Fragments travel at just less than the speed of light.

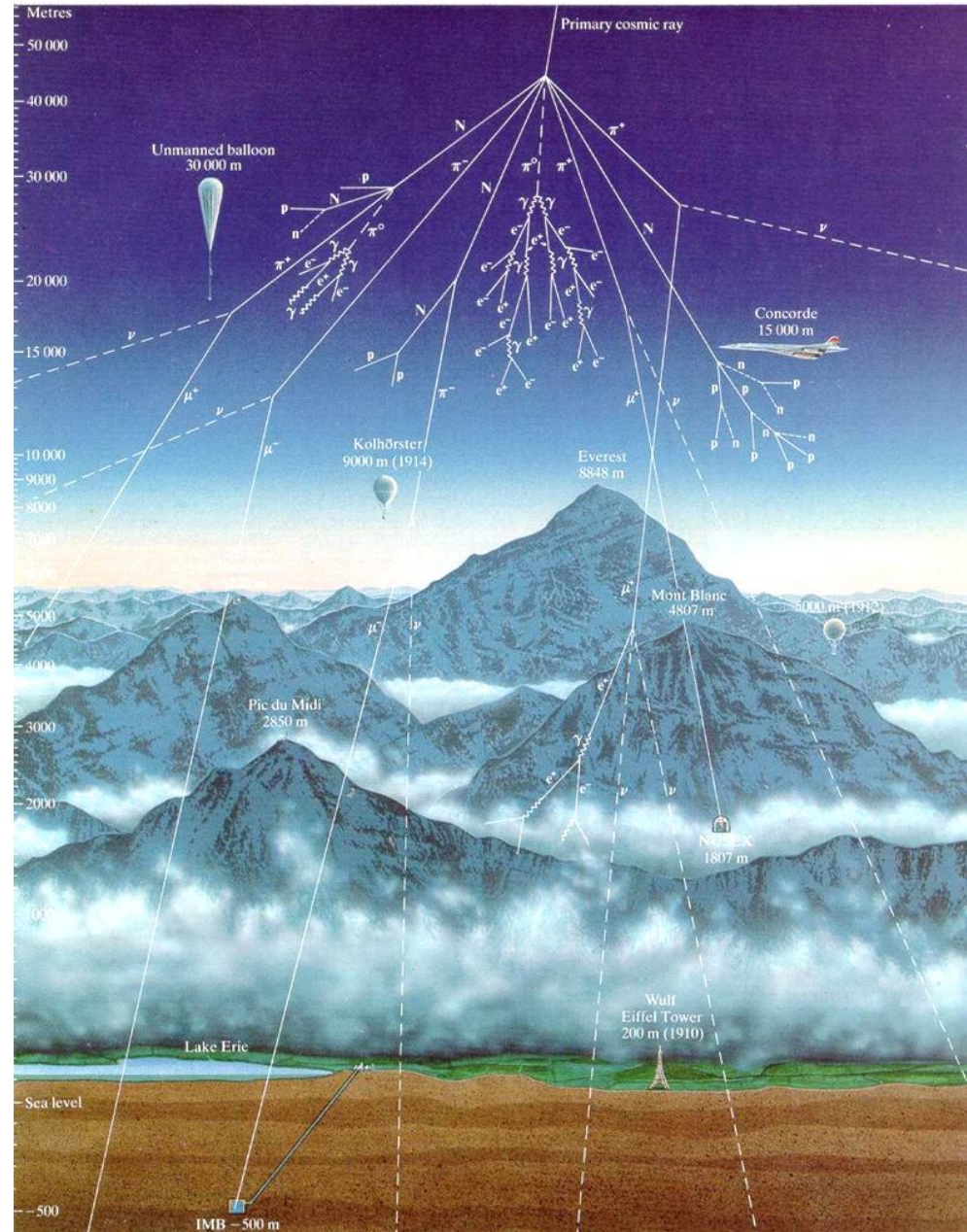
What are Muons?

- Elementary particles from the same family as electrons.
- Same charge as an electron.
- Mass about 200 times that of an electron.
- Unstable and decay with a half-life of 2.2 microseconds.

Cosmic Ray Air Shower

The Particle Explosion

(Close, Marten
and Sutton)

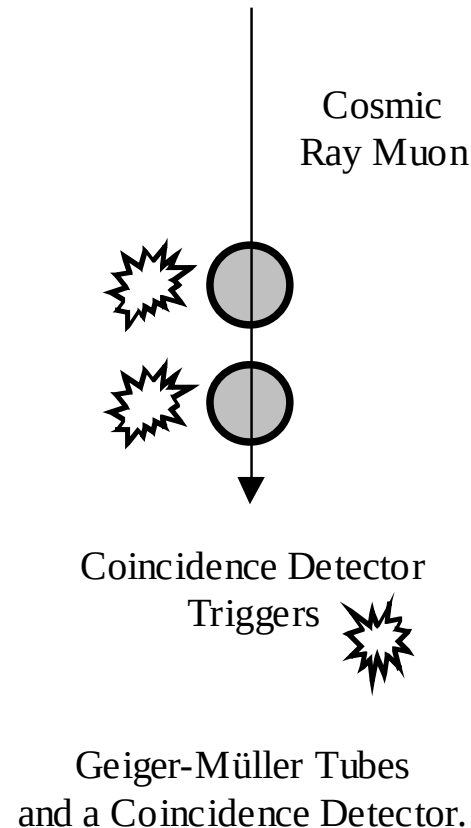


Muons Decay Rapidly

- The number of muons in these showers of particles should decay very rapidly. None should reach the surface of the Earth.
- Consider a muon travelling at just less than the speed of light.
- The surface of the Earth is 60 km below.
- Time to reach the surface at this speed is 200 microseconds.
- Half life of a muon is 2.2 microseconds.
- So, how many half-lives take place in 200 microseconds?
- Number of half-lives = time / half-life = $200 / 2.2$
= 91 half-lives.
- So the fraction remaining at the surface will be 0.5^{91}
= 4.0×10^{-28} the original number.
- From this, we do not expect any muons to reach the surface.
- They should have all decayed during their journey.

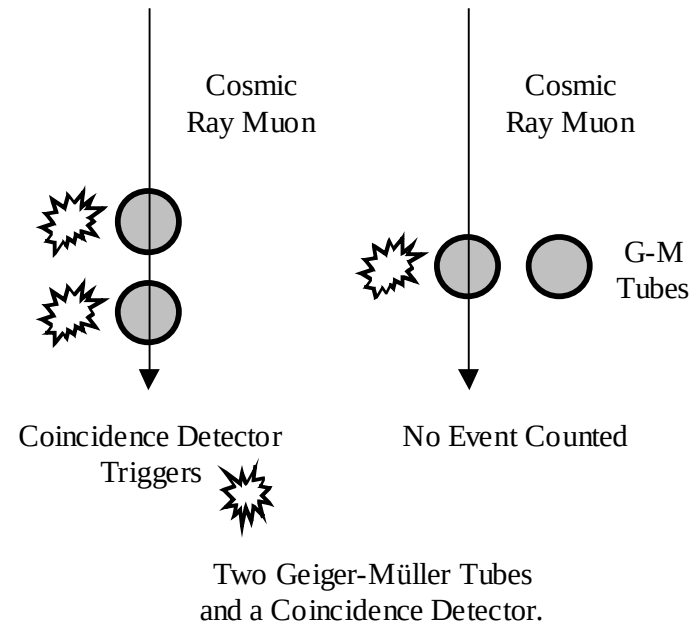
Detection of Cosmic Ray Muons

- Use of simple coincidence detector.
- Two Geiger-Müller tubes, positioned one above the other.
- The outputs from the tubes are connected to a coincidence detector (an AND gate).
- The counter only operates when both tubes trigger within about a microsecond of each other.
- If the system is left to count for many minutes, a count rate of about 4 events per minute is observed.



Are we detecting Muons?

- If the tubes are now placed side-by-side, the count rate falls to near zero.
- You could do this at school with two independent counters and use your pupils as coincidence detectors!!
- The result suggests that the particles that are coming from above. It is most likely that these particles are muons.
- However, this is a puzzle. All the muons should have decayed before they reached the surface of the Earth.



Time Dilation Calculation

- Observed half-life = Proper half-life / $(1 - v^2 / c^2)^{1/2}$
where v = speed of muon and c = speed of light.
- Observed half-life = $2.2 / (1 - (2.9984 \times 10^8 / c)^2)^{1/2}$
= 67.4 microseconds.
(For muons travelling at 2.9984×10^8 m/s.)
- Recall that it takes 200 microseconds for the muons to travel down to the surface.
- From our perspective on the ground, in these 200 microseconds we see only about 3 half-lives going by.
- This is why some muons reach the surface of the Earth.
- On this basis, 1 in 8 muons are expected to reach the surface because their 'moving half-life clocks' run slow.

Summary

- Moving clocks run more slowly.
- Air Showers are created by Cosmic Rays.
- Unexpectedly, some Muons in the Showers reach the ground.
- Time Dilation slows their decay as seen by an observer on the ground from 2.2 to 67 microseconds.

Test

- 1) You run past a radioactive source and you measure its half-life. Will it be:
a) Increased b) Decreased. c) Unchanged.
- 2) A person runs past you carrying a radioactive source and you measure its half-life. Will it be:
a) Increased b) Decreased. c) Unchanged.
- 3) If you did not know about Special Relativity, why would you expect no cosmic ray muons to reach the surface of the Earth?
a) They travel too slowly. b) They have a very short half-life
c) They are absorbed by the air. d) They have a negative charge.
- 4) Why do some cosmic ray muons reach the surface of the Earth?
a) They travel at just less than the speed of light.
b) A very large number are created at the top of the atmosphere.
c) Their half-lives appear to be lengthened by their speed
d) The air is not very dense so it does not absorb them.

References

- Change in spectrum of moving atoms.
H E Ives and G R Stilwell, J Opt Soc Am, XXVIII, 215 (1938).
- Muons can be detected at the surface of the Earth.
B Rossi and D B Hall, Phys Rev, 59, 223 (1941).

The 1905 Timeline

In 1905, Albert Einstein published papers on:

- The Quantum Nature of Light and the Photoelectric Effect. 18 March 1905.
- Avogadro's Number and the Size of Molecules. 30 April 1905. (Doctoral Thesis in 1906.)
- The theory of Brownian Motion. 11 May 1905 and 19 December 1905.
- The Special Theory of Relativity. 30 June 1905.
- The interchangeability of Mass and Energy ($E = mc^2$). 27 September 1905.

Mr Alan C Pickwick

- Manchester Grammar School, Old Hall Lane, Manchester, M13 0XT, UK.
- I teach physics at Manchester Grammar School. The school was founded in 1515 and is an independent, fee-paying school for boys of ages 11 to 18 years. There are 1440 boys on roll, each of whom has passed our demanding academic entrance examination. Almost all boys go on to university and each year a little less than one quarter of the leavers (40 boys) win places at the universities of Oxford or Cambridge. The school prides itself in its sport, music and drama as well as its fund-raising for charity and its work in the community.
- I have a BSc in Physics and an MSc in Radio Astronomy from The University of Manchester.
- I am a founder member and currently Secretary of the European Association for Astronomy Education and immediate past Chair of the Education Committee of the Royal Astronomical Society.