Muons on Mt. Mitchell - Time Dilation is REAL

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Edited by Bill Gabella and Med Webster

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Abstract

Bruno Rossi's measurements of the cosmic ray flux in Denver and on Mt. Evans is one of the earliest convincing demonstrations that time dilation is a real effect. The Vanderbilt Quarknet group undertook a modern version of that classic experiment comparing the flux in Nashville with the flux near the peak of Mt. Mitchell, North Carolina. The altitude difference is about a mile for both the Colorado and the Tennessee sites. Two experiments were done using two Quarknet telescopes with the top and bottom pairs of scintillators separated by 112 cm: 1) Comparison of the flux at the two altitudes with only 8 cm of concrete in the telescope at both elevations and 2) Insertion of an additional 84 cm of concrete at the Mt. Mitchell elevation to remove the muons which would have stopped by "friction" (ranged out) in the air between the two elevations. The Nashville measurements were done in a garage July 6-8 and the high altitude measurements were done in a picnic shelter near the peak of Mt. Mitchell on July 10. If there were no time dilation and accounting for the decay time of the muon, the flux should be 12.6 times higher on Mt. Mitchell. We find that the flux on the mountain is 1.58 times higher than in Nashville with 4 cm of concrete in the telescope at both elevations, and only 1.14 times higher with the additional concrete to match the effect of the air column. The increase in the muon lifetime in our frame of reference is clearly needed to account for the much higher muon survival fraction.

1 Friday Schedule, Assignments

1. Altitude summary and Muon properties
2. Calculate the expected flux ratio at the two altitudes if there were no time dilation -(7 to 10 has been rumored). No dilation team: James and Terry
3. Why insert 21 bricks between the counters for the Mt. Mitchell Run, or more specifically 2 bricks in Nashville and 23 bricks on Mt. Mitchell? Bricks team: Meaghan, Kim and Aimee

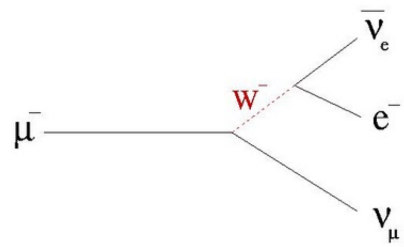

Figure 1: Decay of a Negative Muon

4. Combine counts from run files and calculate rates with errors. What are the observed ratios of rates at Mt. Mitchell to rates in Nashville for 1) two bricks in each and 2) 23 bricks on Mt. Mitchell and 2 bricks in Nashville. Rates team: Diana and Bill H.

5. Write the conclusions. Bill G. and Med, after the above results are in.

2 Altitudes

Bill G. looked at the responses to the "DG" command which displayed the GPS data and finds:

Mt. Mitchell:	1995.7 ± 0.5 meters $= 6547.6 \pm 1.5$ feet
	38 data points on 10 July 2013
Nashville:	325.1 ± 0.8 meters $= 1066.5 \pm 2.6$ feet
	26 data points on 6-7 July 2013

3 Muon properties

1. The muon mass is 105.66 MeV.

2. The mean decay time (1/e) is 2.197×10^{-6} seconds and the half-life is 1.523×10^{-6} seconds.

3. The dominant (nearly 100%) decay mode is to a muon neutrino and a virtual W, with the W decaying to an electron and an electron (anti-) neutrino as shown for a μ^- in the Feynman diagram, figure 1.

All of our runs are done with two bricks in order to eliminate counts from the soft component of the cosmic radiation. If one makes a plot of telescope counting rate *vs.* thickness of bricks, the decrease is much steeper for the first few centimeters than for thickness from about 5 cm to several meters. The

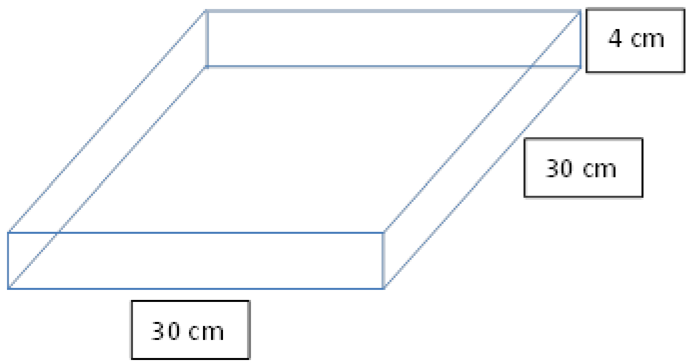

Figure 2: Dimensions of a brick

particles thus eliminated probably are not muons but are a mixture of knock-on electrons and strongly interacting particles. By working with two bricks as our basic configuration we are eliminating these as well as removing those very low energy muons which are very close to stopping.

4 A mile of air - equivalent in bricks

Muons are charged and lose energy as they pass through matter. Some muons at Mt. Mitchell have too little energy to pass through all the air between the Mt. Mitchell altitude and the Nashville altitude. The change in flux with altitude is due to this loss as well as to decay. We wish to measure the loss of flux due only to muon decay. If we put bricks between the counters at Mt. Mitchell, we can stop, and thus not count, those muons. The difference in counting rate between the two altitudes will then be due to decays.

The brick size was chosen to completely cover a scintillator paddle. The bricks are made of concrete and dimensions are shown on Figure 2.

1. Density of air is 1.205 g/l at 1 atm, dry air, 20°C.
2. Air pressure above sea level can be calculated[1] as:

   $$\mathrm{p} = 101325(1 - 2.25577 \times 10^{-5}\,\mathrm{h})^{5.25588}$$

   where p is air pressure (Pa) and h is altitude above sea level (m).
3. The energy lost per distance (dE/dx) for dry air is $1.815\,\mathrm{Mev\,g^{-1}\,cm^{2}}$ according to Physical Review D.
4. Nashville
   – Elevation: 325.1±0.8 m
   – Pressure: 0.9621 atm or 14.14 psi

[1]This formula is for an adiabatic atmosphere. References and web sites for calculators are given in the appendix.

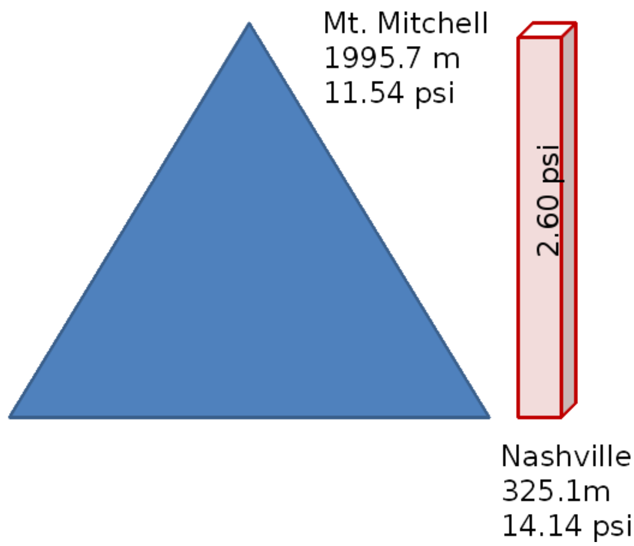

Figure 3: Air pressure at top of Mt. Mitchell and at Nashville and the additional column of air which muons detected at Nashville have had to penetrate.

5. Mt. Mitchell
   – Elevation: 1995.7±0.5 m
   – Pressure: 0.7850 atm or 11.54 psi

6. Ratio of pressure at Mt. Mitchell to Nashville pressure is 0.816.

7. The pressures were calculated according to the elevation and the formula listed earlier.

8. The difference in pressure[2] is 2.60 psi or 183.0 g/cm^2.

9. The density of the brick is 2.3 g/cm^3 (density of concrete according to Physical Review D.

10. With a thickness of 4 cm as shown in figure 2, the mass per unit area was calculated to be: 2.3 g/cm$^3\times$ 4 cm = 9.2 g/cm^2.

11. The energy lost per distance (dE/dx) for concrete is $1.711\,\mathrm{Mev\,g^{-1}\,cm^2}$ according to Physical Review D.

12. The energy loss to dry air is $1.815\,\mathrm{Mev\,g^{-1}\,cm^2}$ according to Physical Review D.

13. The energy loss in penetrating the column of air as shown in figure 3 is $1.815\,\mathrm{Mev\,g^{-1}\,cm^2} \times 183.0\,\mathrm{g/cm^2} = 332.1\,\mathrm{MeV}$.

[2]These are actually the supported mass per unit area and are less than pressure by a factor of g.

14. The equivalent mass per sq cm for concrete is $194.1\,\mathrm{g/cm^2}$ which is calculated using the energy loss for concrete:

$$(332.1\,\mathrm{MeV})/(1.711\,\mathrm{Mev\,g^{-1}\,cm^2}) = 194.1\mathrm{g/cm^2}$$

15. By calculating the amount of energy needed to go through the column of air (332.1 MeV) divided by the loss (friction) of concrete ($1.711\,\mathrm{Mev\,g^{-1}\,cm^2}$) we got 194.1 $\mathrm{g/cm^2}$ necessary to substitute for the column of air. Dividing that by the pressure (or column density) of a brick (9.2 $\mathrm{g/cm^2}$), we calculated that we would need 21.1 bricks to create the equivalent of the column of air between Nashville and Mt. Mitchell $(194.1\,\mathrm{g/cm^2})/(9.2\,\mathrm{g/cm^2}) = 21.1$.

5 No Dilation Team Slide

If time and the duration of time intervals were the same for everyone, as envisioned by Newton, we could calculate the time interval for a moving particle simply from its speed and the distance it travels during the interval. If the particle can decay, we can then calculate the fraction of such particles which survive by comparing the time interval to the lifetime or to the half life of the particle. Our goal is to do this Newtonian calculation for muons at Mt. Mitchell to see what fraction of the Mt. Mitchell flux we should expect to find in Nashville if there were no time dilation.

The difference in elevation between the Nashville, TN, location (325 m) and the location near the summit of Mt. Mitchell, NC, (1996 m) is 1671 m. The speed, v, of cosmic ray muons is very close to c, the speed of light, and the muons travel a distance, $\Delta\mathrm{z} = 1671$ m = ct where t is the time it takes a muon to travel from Mt. Mitchell altitude to Nashville altitude.

$$\Delta\mathrm{z} = 1671\,\mathrm{m} = \mathrm{ct}$$

gives t=5.57 microseconds. Using the accepted value for the muon mean lifetime, $\tau = 2.197 \times 10^{-6}$ seconds or 2.197 microseconds and the ratio of the counting rate on Mt. Mitchell to the counting rate in Nashville is equal to

$$\mathrm{e}^{\mathrm{t}/\tau} = \mathrm{e}^{2.54} = 12.62$$

.

Those who are more comfortable with half lives than with mean lives can do a similar calculation. The muon half life is 1.523 microseconds and it takes $5.6/1.523 = 3.66$ half lives for the muon descent. The distance traveled in one half life is $\mathrm{ct} = 3 \times 10^8\mathrm{m/s} \times 1.523 \times 10^{-6}\mathrm{s} = 457\mathrm{m}$. If we did our experiment (adjusting the number of bricks) 457 m down from the peak, the counting rate would be half of what it was on the peak. Again down another 457 m (that is 914 m down from the peak) half the previous rate or 1/4 the rate at the top. The next step, down 1371 m would show 1/8 the rate at the top. A fourth step would be down 1828 m from the top and the rate would be 1/16 the rate on the top. But this would be well below our Nashville station - only 168 m above sea level and that must be half way down the Cumberland to Memphis (elevation 82 m) on the Mississippi. Our Nashville rate would be between 1/8 and 1/16 of the rate on the peak. Or more precisely, the muon flux would be $(1/2)^{3.6} = 0.079$ or 1/12.6 of the original flux, as it must.

6 Rates Team Slide

Comparison of the rate with two bricks at the Nashville altitude with the rate on the mountain with two bricks gives us information about the total loss of muons due to both decay and stopping (energy loss - "friction"). The 21 additional bricks were chosen to mimic the energy loss in the column of air, so comparison of the rate with two bricks in Nashville with the rate with 23 bricks on the mountain gives information on the loss due only to decays and thus directly on the need for time dilation. The efficiencies of the two counters differ slightly, so it is better to use the same counter at both altitudes when making such a comparison. Unfortunately the counter with 23 bricks had connector problems and there were several times when one of the paddles stopped counting. These times were identified during data acquisition by watching the plots at the bottom of the scalers screen and corrective action was taken. These dead times can be identified off line by looking at the singles rates which are reported every 100 seconds and recorded in the disk file. Events occurring during these dead times are not counted and time is not accumulated during those intervals. Counts and times for all other files were available for this writing session, but the corrected data for the 23 brick run on the mountain were not available until several days later.

The rates and errors for runs done in Nashville are computed by the program which reads the data files. The runs on Mt. Mitchell had to be broken into pieces because the power had to be turned off to refuel the generator. The details of combining data from several files for the two units run on the mountain are shown. The two sets of muon counters are designated s6181_10 and s6187_08.

1. For two bricks, Mt. Mitchell - 3 files: s6181_10_20130710_xxx

	Time Interval (hr.)	4-fold Coincidences (events)
000	4.286	8181
001	2.796	5518
003	1.347	2661
Total	8.429	16360

$$\begin{aligned}
Uncertainty\ in\ total\ number\ of\ events &= \pm\sqrt{16360} = \pm 128\ events \\
Counting\ rate &= \frac{16360\,events}{8.429\,hours} = 1941\frac{events}{hour} \\
Uncertainty\ of\ counting\ rate &= \pm\frac{128 events}{8.429\,hours} = \pm 15\frac{events}{hour} \\
Counting\ rate &= 1941 \pm 15\ \frac{events}{hour}
\end{aligned}$$

2. For 23 bricks, Mt. Mitchell - 2 files: s6187_08_20130710_xxx

	Time Interval (hr.)	4-fold Coincidences (events)
000	3.521	5636
001	3.047	5071
Total	6.568	10707

   A calculation similar to the preceding yields the counting rate: 1630±16 events/hour.

3. For two bricks, Nashville - 1 file: s6187_08_20130706_001
   4-fold coincidence rate: 1426.5±5.8 events/hour

4. For two bricks, Nashville - 1 file: s6181_10_20130707_001
   4-fold coincidence rate: 1227.2±7.4 events/hour

7 Conclusions

The fractional muon increase due to both decay and stopping by energy loss is the ratio of the rates with only two bricks for counter s6181_10:

$$\frac{1941 \pm 15}{1227.2 \pm 7.4} = 1.582 \pm 0.015$$

The fractional muon increase due only to decay is the ratio for counter s6187_8 with 23 bricks on Mt. Mitchell to 2 bricks in Nashville:

$$\frac{1630 \pm 16}{1426.5 \pm 5.8} = 1.143 \pm 0.012$$

Note that removing the muons which stop (range out) by "friction" accounts for about three fourths of the loss (1.143 is about 1/4 of the way from 1.0 and 1.582). One quarter of the missing muons are lost by decay while the other three quarters of the loss is mainly muons with too little energy to penetrate the air column between the two altitudes. So have we really proven the need for time dilation at the confidence level that our measured ratio, 1.143 ± 0.012, is not equal to our no-time-dilation theory ratio, 12.62?

The use of standard deviations to describe confidence in a result became popular conversation as we watched confidence in the Higgs bumps grow and the norm of four or five standard deviations seemed to be an important standard for establishing a new idea. An incredibly naive calculation tells us that our result is (12.62 - 1.143)/0.012 = 1017 standard deviations away from the no dilation prediction. Continuing with absurd calculations, the probability of observing such a fluctuation is $10^{-224599}$. One should rarely believe such extreme statistical statements; there usually are additional contributors to the error which were ignored. This quoted uncertainty comes entirely from the counting statistics. Other errors such as the quoted muon lifetime, the altitudes, and the change in alignment of the counters between the two runs, are small but would have to be considered long before we could talk intelligently about such very, very small probabilities. We have a very convincing result. The statistical contribution to the uncertainty in our conclusion that time dilation is a real effect is utterly negligible and these other contributions are very small. Ending on a whimsical note, the probability that all nine of us authors are insane is surely much greater than $10^{-224599}$ and we did not take that into account in our probability calculation!

8 References

The most appropriate reference for this report is the nostalgic reminiscence which Bruno Rossi gave at the International Symposium on Particle Physics in 1980:

Rossi, Bruno (1980), "The Decay of "Mesotrons" (1939-1943): Experimental Particle Physics in the Age of Innocence", in Brown, Laurie M., International Symposium on the History of Particle Physics, Fermilab, 1980, Cambridge: Cambridge University Press, pp. 183205, retrieved 11 January 2013, "In The Birth of particle physics. ISBN 0521240050"

9 Appendix

The formula is given at
http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html
and agrees with the US Standard Atmosphere (1976)
http://en.wikipedia.org/wiki/U.S._Standard_Atmosphere.

Calculators may be found at
http://aero.stanford.edu/stdatm.html
or at
http://www.digitaldutch.com/atmoscalc/.

We were misled by the calculator at
http://www.calctool.org/CALC/phys/default/pres_at_alt
which is based on an isothermal atmosphere at an unreasonably cold temperature and predicts a significantly steeper fall off of pressure with altitude.