Measuring the attenuation of cosmic ray muons in water

Mero Elmarassy*
MIT Department of Physics
(Dated: May 8, 2025)

Earth is constantly being bombarded by cosmic rays produced in space. Through interactions with atomic nuclei in the atmosphere, these rays produce particles that can reach the surface and impact particle physics experiments. To combat this, many of these experiments are done in labs deep underground, where the background particles are unlikely to penetrate. [1]

The amount of shielding a lab achieves is usually measured in terms of the meter water equivalent (m.w.e.). Most of the deeply penetrating particles are muons, so it is useful to measure the attenuation of muons in water which can be used to estimate how well a lab is shielded from cosmic ray backgrounds. In this paper we obtained a muon water attenuation rate of $0.039 \pm 0.007\text{m}^{-1}$.

I. RELEVANT THEORY

I.1. Cosmic rays

Cosmic rays are high energy particles produced in space. Most cosmic rays are either ionized hydrogen or helium nuclei, but they can sometimes be composed of heavier particles. The cosmic rays that reach Earth originate from many sources, including the sun, other stars, supernovas, or even farther sources in other galaxies. [2]

When a cosmic ray reaches the atmosphere of the Earth, there are many effects that result in different kinds of particles being produced. These can include photons from Bremsstrahlung or electrons from pair production and decays of heavier particles. However, the most important effect in our analysis is the production of muons, which are the most penetrating and therefore most important to shield against.

Muons are mainly produced when a cosmic ray interacts with an atomic nucleus, producing a meson such as a pion or a kaon. Since mesons are composed of quarks, they interact via the strong force and quickly decay into a muon of the same charge and a muon neutrino. The muons, which only interact via the weak force, have a much longer lifetime and are able to reach the Earth's surface. Therefore, they comprise the main part of the background radiation due to cosmic rays that we observe.

I.2. Attenuation of cosmic ray muons

Attenuation is a measure of the rate of loss of flux intensity through a medium. As muons (or other particles) travel through a medium, they gradually lose energy and are absorbed by the medium, causing the rate to drop as a function of distance traveled.

The attenuation depends on the medium; for a denser medium the attenuation is usually greater meaning that flux drops more quickly. In the atmosphere, where the density is relatively low, background particles can travel large distances. However, in a much denser medium like water, they are quickly stopped.

* mero@mit.edu

I.3. Theoretical angular distribution of cosmic ray muons

The flux of cosmic ray muons also depends on the angle relative to the normal of the surface, mainly due to two effects.

1. **Lifetime of the muon:** the muon has a relatively short lifetime of roughly 2.2μs, but some muons are able to reach the surface before decaying due to relativistic length contraction which increases their travel distance.

   However, due to the fact that near-vertically incident muons travel a much shorter distance than muons from wider angles, a smaller fraction of them decay before reaching the surface. This skews the distribution, making vertically-incident muons more likely.

2. **Attenuation in the atmosphere:** as previously discussed, muons lose energy and are eventually absorbed as they travel through a medium. While the atmosphere is not very dense, this effect is still significant due to the large distances traveled. Since vertically incident muons travel shorter distances, they are attenuated less and are more likely to reach us.

Due to these two main effects, the expected theoretical distribution of the muon rate as a function of azimuthal angleθ is [2]

$$\frac{dN}{dt}(\theta) \sim \cos^2\theta \tag{1}$$

I.4. CosmicWatch detectors

We used CosmicWatch detectors throughout this experiment, which are small plastic scintillator detectors. When a charged particle passes through the scintillator, it emits radiation that is picked up by the Silicon Photomultiplier (SiPM). This produces a measurable current depending on the amount of energy deposited in the scintillator, and can be recorded by a microcontroller. [2]

Two CosmicWatches can be connected to run in coincidence mode. When an event is observed in both detectors within a 1 millisecond window, it is saved as a coincident event. Using coincidence mode filters out many of the unwanted backgrounds, which have very short penetration distances and are unable to trigger both detectors. It also allows us to select for the angle of incident events, which must be within the *cone of acceptance* (see Fig. 1).

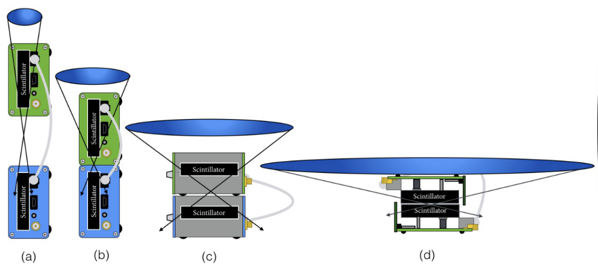

FIG. 1. Cones of acceptance for several coincident detector layouts. Image from [2].

II. EXPERIMENTAL SETUP AND GOALS

In order to measure the attenuation of cosmic ray muons in water, we took rate measurements at several depths. Additionally, an angular correction is needed to account for the nonzero angle of acceptance due to the angular effects discussed in I.3. Therefore, we also took rate measurements at several angles at the surface in order to validate the prediction in (1).

II.0.1. Angular rate measurements

We took data at six angles between 0 and $\frac{\pi}{4}$ for roughly 3-6 hours each. This was done with a large detector separation, which resulted in a low angle of acceptance of about 10 degrees. This was important in order to minimize our angular uncertainty. The other source of angular uncertainty was our measurements of the detector orientation angle, which was done with trigonometry. However, this was relatively small compared to the angle of acceptance.

The reason for only checking between angles 0 and $\frac{pi}{4}$ was to obtain the best possible data for our measurements. Our submersion data used an angle of acceptance of $\frac{\pi}{4}$, so there was no need to verify the distribution for higher angles. This allowed us to spend more time at the angles we needed in our corrections, allowing us to obtain the best possible statistics in our timeframe.

II.0.2. Submersion rate measurements

This was the fun part of the experiment! We used a steel submersible chamber from the lab, pictured in Fig. 2. We began by taking measurements at the Charles River, where we were able to take seven roughly uniformly spaced measurements at depths between 0 and $\sim$ 10m deep. We then decided it would be interesting to see attenuation data from a deeper submersion, so we repeated our measurements at White Pond where we were able to go almost twice as deep. Finally, we did measurements off the Charles River dock up to 3m in order to see the attenuation in shallow water (which is different from in deeper water).

The resulting data is summarized in Fig. 3, where the data has been normalized by the zero-depth count rate to account for day-to-day variation in the rates.

FIG. 2. Steel submersible chamber used to make underwater rate measurements.

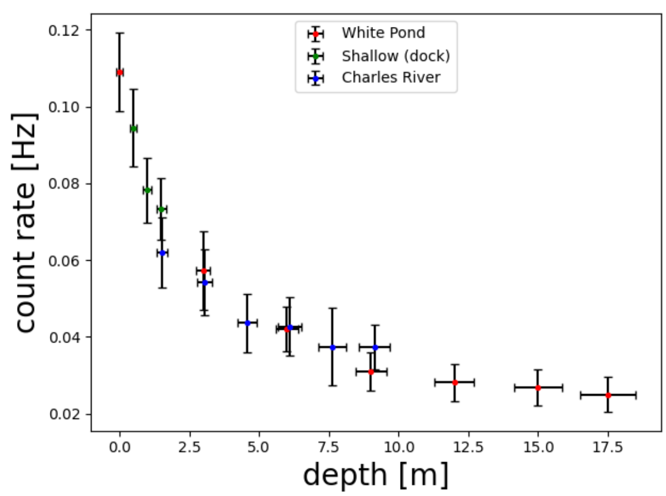

FIG. 3. Submersion muon rate data from Charles River, White Pond, and the dock

III. DATA ANALYSIS

III.1. Muon attenuation (uncorrected)

As a start, let us compute the muon attenuation for the data without angular corrections, which will give us an idea of what to expect when we do the corrections.

Assuming the particles lose a constant amount of energy per unit distance traveled, the flux of particles as a function of distance traveled should be a decaying exponential:

$$\frac{\partial N}{\partial t}(d) = Ae^{-\mu d} \tag{2}$$

where μ is the attenuation rate. However, our detectors do not observe just one kind of particle. While we observe deeply penetrating muons, we can also observe electrons or other charged particles that do not travel as far in water for various reasons. Therefore we expect to see a mixture of two fluxes: one that quickly decays and corresponds to background, and another that decays much more slowly and corresponds to cosmic ray muons.[2]

Therefore our fit function will be

$$\frac{\partial N}{\partial t}(d) = Ae^{-\mu_1 d} + Be^{-\mu_2 d} \tag{3}$$

where A and B are the initial fluxes of the background and muon components respectively. The results of the fit are summarized in Fig. 4.

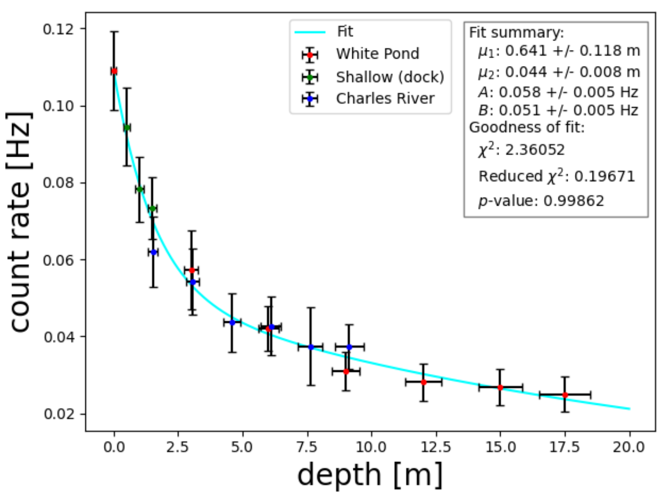

FIG. 4. Initial fit to submersion rates (without angular corrections)

We will come back to these results after doing the angular correction to make sure that it makes sense.

III.2. Validating the theoretical angular distribution

Recalling the form of the theoretical distribution (1), we can fit to our experimental data obtained in II.0.1.

We performed a fit with a more general $\cos^2$ function given by

$$\frac{\partial N}{\partial t}(\theta) \sim A\cos^2(\omega\theta + \phi) \tag{4}$$

where A is a normalization for the rate and ω and ϕ are additional degrees of freedom that we expect to be 1 and 0 respectively if the distribution is correct. The results of this fit are summarized below in Fig. **??**.

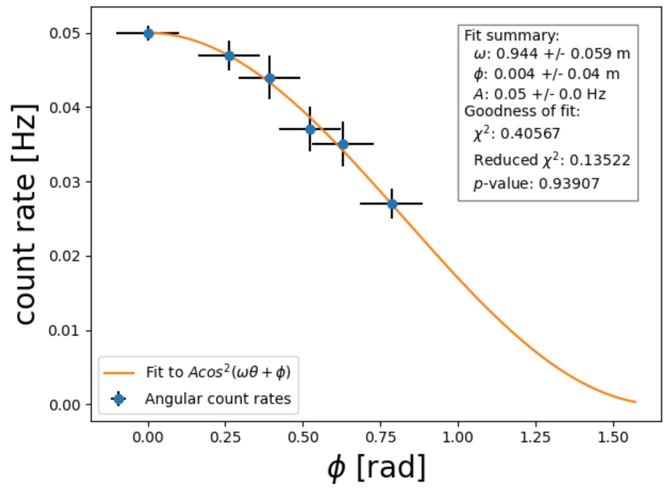

FIG. 5. Fit to angular coincidence rates agrees with theoretical $\cos^2$ prediction.)

Within the uncertainty of the fit, both ω and ϕ agree with their theoretical values. Therefore, we can claim that the theoretical distribution of angular rates is in good agreement with our observations for $0 \leq \theta \leq \frac{\pi}{4}$.

III.3. Deriving the angular corrections to the rate

Throughout this section, we use θ to refer to the azimuthal angle and ϕ for the polar angle. When correcting for the angle of acceptance of the coincident submerged setup (which lies on the θ axis), there are a few main effects to consider:

1. **Detector Shadow:** the probability of a coincident event as a function of (θ, ϕ) is proportional to the area of the "shadow" of the top scintillator onto the bottom one.

2. **Azimuthal rate distribution:** as discussed earlier, the rate varies as a function of angle according to $\sim \cos^2\theta$.

3. **Angle-dependent path length:** particles which are near-vertically incident ($\theta \ll 1$) travel a much shorter distance through the water compared to particles that come in at large θ.

Since coincident events occur only when a particle intersects both scintillators, the probability of detecting a particle incident with angles $(\theta, \phi$ is proportional to the area of the "shadow" shown in Fig. 6.

Using trigonometry, we computed the proportion of the plate covered by a shadow as

$$P(\theta, \phi) = \max\left[0, (1 - \alpha\cos\phi\tan\theta)(1 - \alpha\sin\phi\tan\theta)\right] \tag{5}$$

where $\alpha = \frac{h}{w}$, the ratio of the height between the scintillators to the width of the scintillators. In our submersion chamber we had $h = w = 5$cm, giving $\alpha = 1$.

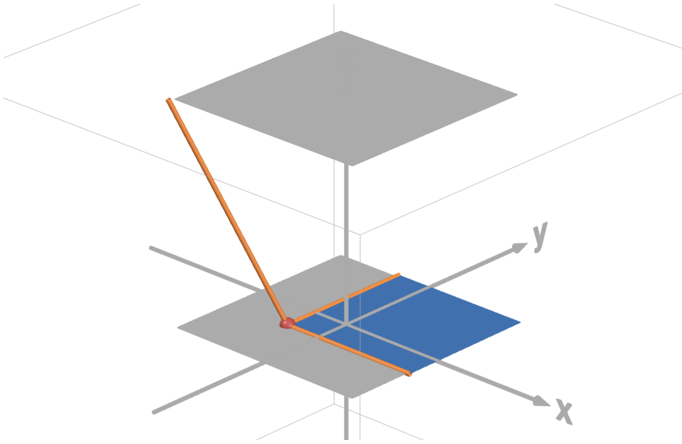

FIG. 6. The two gray squares represent the scintillators of the CosmicWatches. When a muon ray (orange line) is incident at angle (θ, ϕ), the probability it is detected is proportional to the shadow area (blue region).

Next, the distance traveled through the water is not always equal to the depth, since particles incident at an angle travel more distance.

At a depth of d, the distance traveled for a particle incident at azimuthal angle θ is actually $d\sec\theta$ using some trigonometry. As a function of angle, (3) becomes

$$\frac{\partial N}{\partial t}(d,\theta) = Ae^{-\mu_1 d\sec\theta} + Be^{-\mu_2 d\sec\theta} \tag{6}$$

Combining the three effects we discussed, we obtain the differential muon rate as a function of the angles:

$$\frac{\partial^3 N}{\partial t\partial\theta\partial\phi} = P(\theta,\phi)\cos^2\theta\left(Ae^{-\mu_1 d\sec\theta} + Be^{-\mu_2 d\sec\theta}\right) \tag{7}$$

We then integrate over the angles θ and ϕ to obtain the corrected rate as a function of depth:

$$\frac{\partial N}{\partial t}(d) = \int_0^{\frac{\pi}{2}}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{\partial^3 N}{\partial t\partial\theta\partial\phi}\sin^2(\theta)d\phi d\theta \tag{8}$$

IV. CORRECTED ANGULAR FIT

We fit the corrected fit function (8) to our submersion data from II.0.2. The integral was done numerically with Numpy in order to perform the fit.

The results are summarized in Fig. 7.

We may now compare this fit to the original, uncorrected fit to verify that it makes sense. As expected, the calculated muon attenuation rate μ_2 is smaller than before. This is due to the fact that this method corrects for the larger distance traveled, while the uncorrected version did not. Therefore the uncorrected version attributed more of the rate drop to attenuation, when in fact it was due to a larger travel distance.

Additionally, we find that the ratio $\frac{A}{B}$ agrees between the two methods within uncertainty. This is due to the fact that we expect roughly the same proportion of background

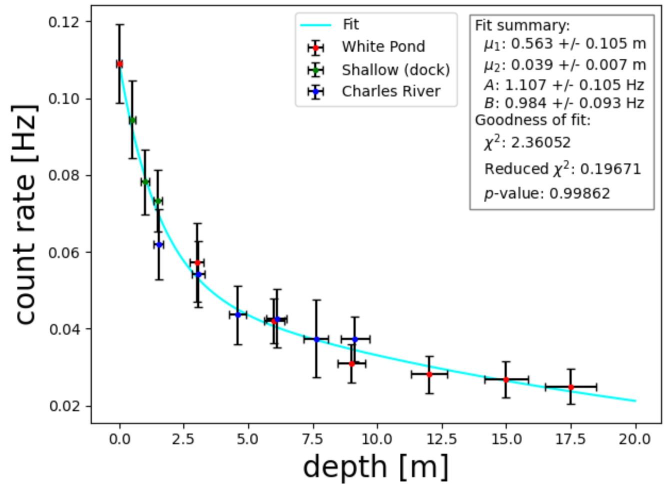

FIG. 7. Fit to submersion data with angular corrections from III.3.

and muon components between the two methods. (The individual values of A and B are not meaningful on their own here, only their ratio).

V. CONCLUSION

We found a muon attenuation coefficient of $\mu_2 = 0.039 \pm 0.007\text{m}^{-1}$, which agrees with known literature values for the attenuation of muons in water [1](using the meter water equivalence). Additionally, our angular corrections behaved as expected, slightly reducing the value of our computed muon attenuation rates. This is good evidence that the angular correction method employed here was valid. Additionally, corrections would be more significant for lower values of α, where the angles become even more extreme.

ACKNOWLEDGMENTS

Thank you to Aaron Pilarcik for taking us on data-taking trips at the Charles and White Pond! This data would not have been possible to obtain without his help.

[1] D. Mei, arXiv (2005).

[2] M. D. of Physics, *8.13 CosmicWatch Lab Manual*, MIT (2024).