Determination of the Scattering Length of 1.03 and 1.015 Refractive Index Matsushita Aerogel for the Kaon Aerogel Cherenkov Detector at the Thomas Jefferson National Accelerator Faciltiy

Abstract:

The purpose of this experiment is to determine the scattering length of aerogel produced by Matsushita Electric Works for use in Cherenkov detectors at Jefferson Lab. These tiles detect particles because when a particle passes through a medium faster than light travels in that medium it emits light and slows down. Cherenkov detectors detect particles via the presence of this Cherenkov radiation, and the cone of radiation emitted as the particle moves can be used to determine the momentum and hence mass of the particle, identifying the particles. Because light traveling through aerogel is fundamental to their use as Cherenkov counters, knowledge of the optical properties of aerogel is essential. The property tested was scattering length, a measure of the likelyhood that a photon traveling throught the material will be scattered. This property was tested at a variety of refractive indices of aerogel. This was tested by shining a collimated beam of light through aerogel tiles and measuring the resulting change in intensity with a photomultiplier tube. A blue LED with peak wavelength of 470nm was used to test these properties. In visible and longer wavelengths, scattering in aerogel occurs at shorter distances, and absorption at longer distances. While both processes are always occurring, scattering will has a great effect over large distances, and absorption has a very small effect over shorter distances. Scattering will be measured first, at short aerogel thicknesses of 1-5 cm, where absorption will not have much effect. In this experiment the scattering length of 1.03 and 1.015 refractive index aerogel was determined.

Introduction:

Silica aerogels are produced by replacing the liquid portions of a silica gel with gasses, typically through supercritical drying, a process which takes advantage of the indeterminacy of state under certain conditions to circumvent the effects of surface tension while drying which could harm the silica structures of the aerogel. Aerogels have the lowest densities of all solids, and also the lowest refractive indices. The aerogel tested in this experiment was produced by Matsushita Electric Work Fine Cereamics Center. Aerogel is typically hydrophilic, which leads to aerogel tiles taking in moisture from the air and other surfaces in contact with it. This leads to a decrease in optical quality of the aerogel over time, and is generally responsible for the relatively short lifespan of aerogel tiles in detectors. Matsushita Electric Works uses a special treatment during aerogel production which causes the aerogel to become hydrophobic, giving it a longer lifetime. Aerogel has, relative to its mass, a great deal of compressive strength, holding up to 2,000 times its weight. However, aerogel is also very brittle and friable, especially at lower densities. This is because the structure of aerogel consists of winding chains of silica molecules which contain numerous gas pockets. These chains result in gas pockets in aerogel, which contribute to its low density and refractive index. Pores in aerogel typically range in size from 2nm to 30nm, though the distribution of these pores depends on the conditions and methods of the aerogel's production. Aerogel possessing lower refractive index and density tends to have more larger pores. These larger pores are capable of causing Rayleigh scattering, since their size is in the order of magnitude of one tenth that of ultraviolet to infrared light. This is the reason that aerogel appears blue.

As light passes through a material it undergoes two main processes: Absorption and Scattering. The intensity of light passing through a material described by the Beer-Lambert law,

$\frac{I}{I_o}=e^{-\Sigma l}$ where Σ is the attenuation coefficient of the medium and l is the length into the material which a photon has traveled. Attenuation describes the combination of scattering and absorption, and in cases where no scattering is considered, attenuation is taken as the same as absorption. Scattering and absorption lengths are the distances into a material at which the probability that a single photon has been either scattered or absorbed respectively drops to 1/e, and help represent the behavior of light in a medium. These properties are described by the equations $P=e^{\frac{l}{\Lambda_S}}$ and $P=e^{\frac{l}{\Lambda_a}}$ where Λ_S and Λ_a represent scattering and absorption length respectively. The equation relating these properties to the intensity of light some distance into a material is $T=\frac{I}{I_o}=e^{\frac{l}{\Lambda_S}}\cdot e^{\frac{l}{\Lambda_a}}$, where T is the percent transmittance, the ratio of the initial and resultant intensities of the light before and after passing through a material. These properties are key to being able to predict the behavior of light in a medium along with refractive index. Due to the porous structure of aerogel, a consequence of lower density is larger pores appearing more frequently in the structure of the aerogel. This should theoretically have an effect on the scattering length of aerogel, and along with the effect that the change in density has on the absorption length of aerogel change the transmittance of aerogel at different refractive indices. The theoretical dependence of these optical properties on refractive index is because of how refractive index is intrinsically tied to density and the microscopic properties of the aerogel.

The Cherenkov effect occurs when charged particles pass through a dilectric medium faster than light can pass through that medium. When this occurs photons are emitted by the particle as it passes through the medium, the electric field of the particle displacing that of the medium. The light which is emitted by this effect is emitted in a cone creating a wavefront of sorts, as similarly to sonic booms it is unable to propagate at the same speed as that which is causing it. The angle of the cone of radiation is related to the refractive index of the material and the velocity of the particle by the equation $\cos(\theta)=\frac{c}{nv}$ where c is the vacuum speed of light, v is the velocity of the particle, and n is the refractive index of the medium. This relationship facilitates the determination of particle velocity, which can be combined with knowledge from magnetic bending to determine particle momentum to calculate particle mass, which in turn can be used to identify particles. Because Cherenkov detectors center around the detection of light, knowledge of the optical properties of the medium of the Cherenkov counter is essential in order to accurately predict the behavior of light in the detector in order to extract meaning from the recorded data. Charged kaons are particles comprised of a pair of either antiup and strange quarks or up and antistrange quarks. They are a meson characterized by their strangeness and decay into pions. The recently constructed Kaon Aerogel Detector for Hall C at Jlab is part of a greater spectrometer designed to identify the particles from nuclear reactions. Because this detector is using aerogel, for the detector to be fully understood so must the optical properties of the aerogel used in the detector.

Materials and Methods:

The relationship used in to deduce the scattering length of aerogel in this experiment is that between transmittance and both scattering and absorption length. Another experiment, designed and carried out by Indra Sapkota, determined the absorption length of the same aerogel using a setup which prevented scattered light from being lost. That knowledge along with transmittance data is used to determine scattering length. For this experiment the goal of the setup was to prevent any scattered light from reaching the receiver, so as to have an accurate measure of how much light had scattered. The light source used was a blue LED with a peak wavelength of 470nm. LEDs emit light at a wide range of angles. Firstly to correct this, the sides of the LED were wrapped to prevent light from being emitted at the more oblique angles. The LED was held in a collimator tube in order to further limit the angles at which the beam of light propagates. A metal plate was bent into a U-shape to hold the aerogel tiles used in the experiment. A shield was designed to place in front of the aerogel holder to prevent excess light from entering into the area where the aerogel was held. At the other end of the holder an aperture was placed the diameter of which was that of the width of the collimated LED beam at after propagaing through the aerogel holder while no aerogel was held within. This setup caused virtually all of the light that passed through the aperture to be that which did not undergo any scattering. Directly after the aperture a PMT was placed to pick up the LED signal after passing through the aerogel. The PMT was placed in shielding and had a thick cloth draped over it to keep electrical signals from interfering with its reading, and to further prevent any outside light from entering the PMT. All of this was assembled inside a darkbox, in order to reduce noise and to keep the PMT safe.

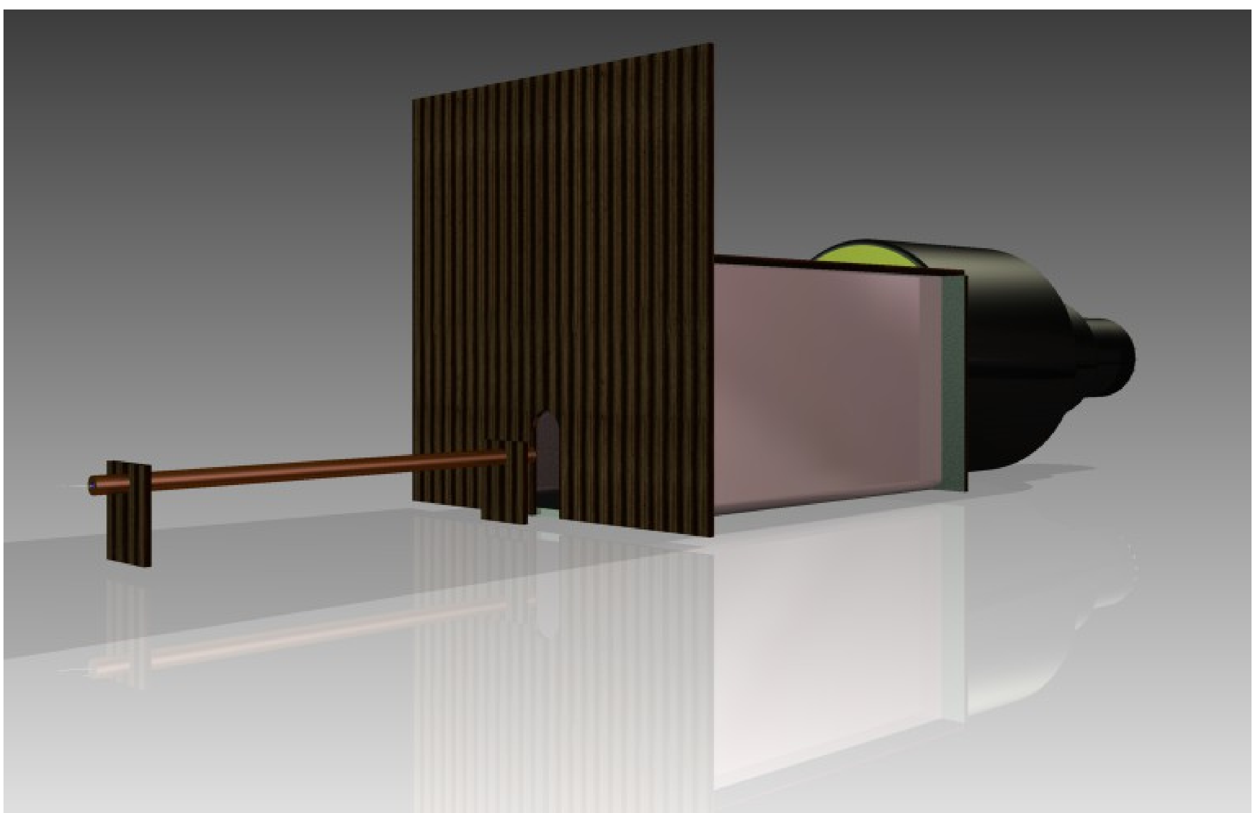

Figure 1: 3D model of the testing setup. Made by Derek Boylan

An electrical signal was provided to the LED with a pulse generator. The PMT measured a signal in the form of current, which was then integrated over the duration of the pulse to record a charge. The data was recorded with CODA, a data acquisition system designed for nuclear physics experiments at Jlab. Data was recorded with no aerogel tiles in the setup as a base measure of the intensity of the light. Data was then taken with various numbers of aerogel tiles in the apparatus, so the intensity of the light after passing through a certain length of aerogel could be compared to the initial intensity, and thus used in calculations to determine scattering length with the equations mentioned earlier. The aerogel tiles used were 11cm x 11cm x 1 cm. At each thickness of aerogel, multiple aerogel tiles were used in combination so as to provide an idea of the properties of the entire population of aerogel and reduce error. Because the aparatus measures all the light that does not scatter, the recorded data fails to account for absorption. For this, data from an experiment by Indra Sapkota was used, which determined the absorption length of aerogel with a refractive index of 1.03 to be 21.35cm +-.47cm. Using the formula relating transmittance to scattering and absorption length, this can be used to extract data on scattering in aerogel from its transmittance. While absorption length was only measured for 1.03 refractive index aerogel, for calculation of the scattering length of 1.015 refractive index aerogel absorption length will be assumed to be directly proportional to aerogel density to give a reasonable estimate of scattering length. Later when absorption of 1.015 aerogel is tested a more accurate value of scattering length can be calculated.

Data:

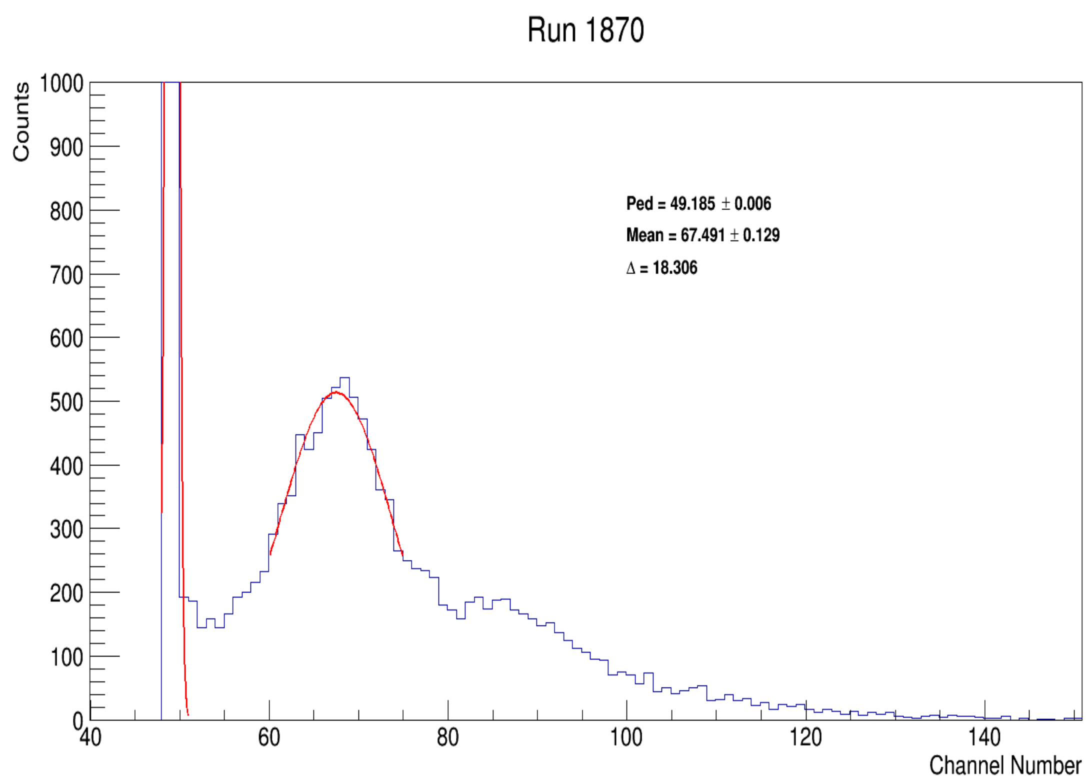

Figure 2: A gain test of the R1584 PMT using 470nm light.

A gain test was initially performed. This used a very small signal from the LED to make a visible difference between the background noise of a signal and the signal produced from a single incident photon. This is the pedistal, and was determined to be 49.185 +-0.006. This was then subtracted from all of the data taken later so as to make the data an accurate representation of the incident light.

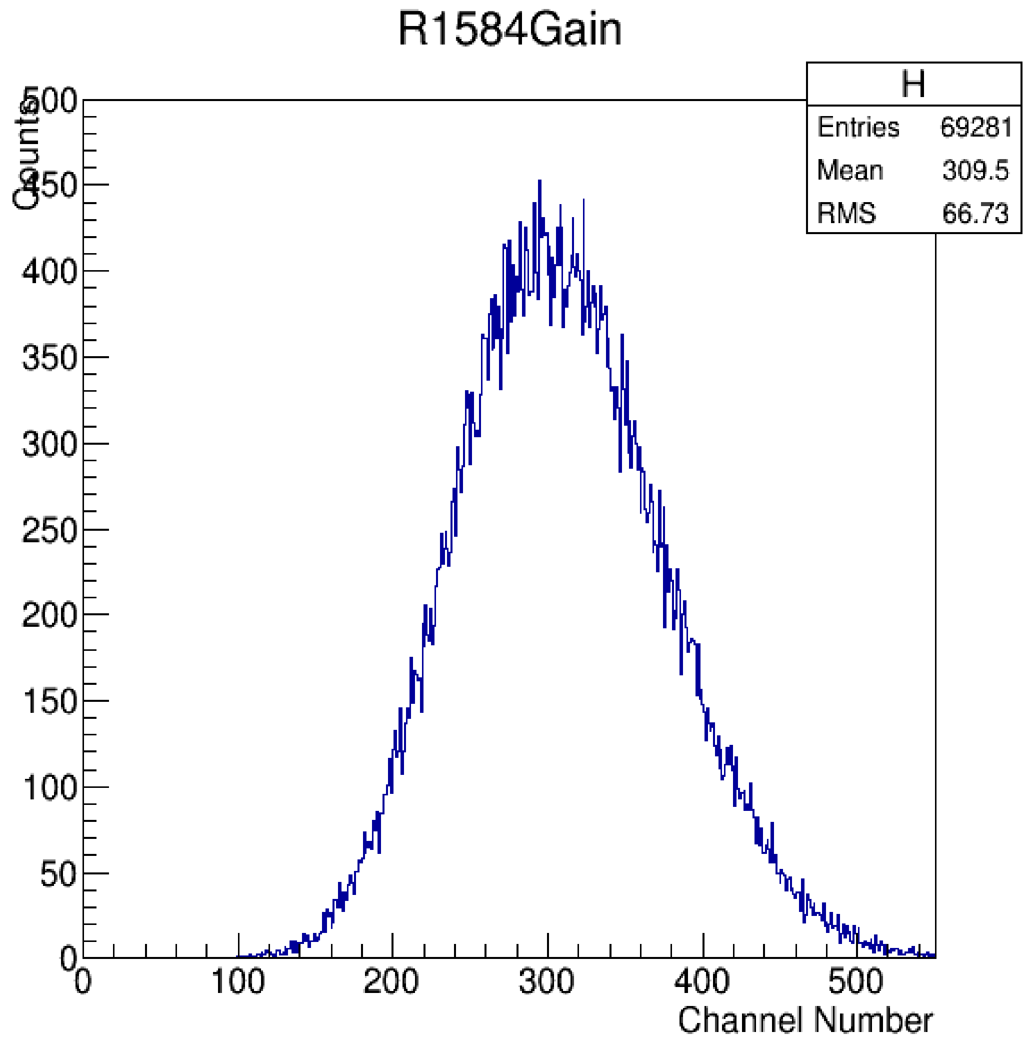

Figure 3: Signal received by the R1584 PMT with no aerogel tiles using 470nm light. This was a test performed to establish a baseline intensity for experiments on 1.015n aerogel.

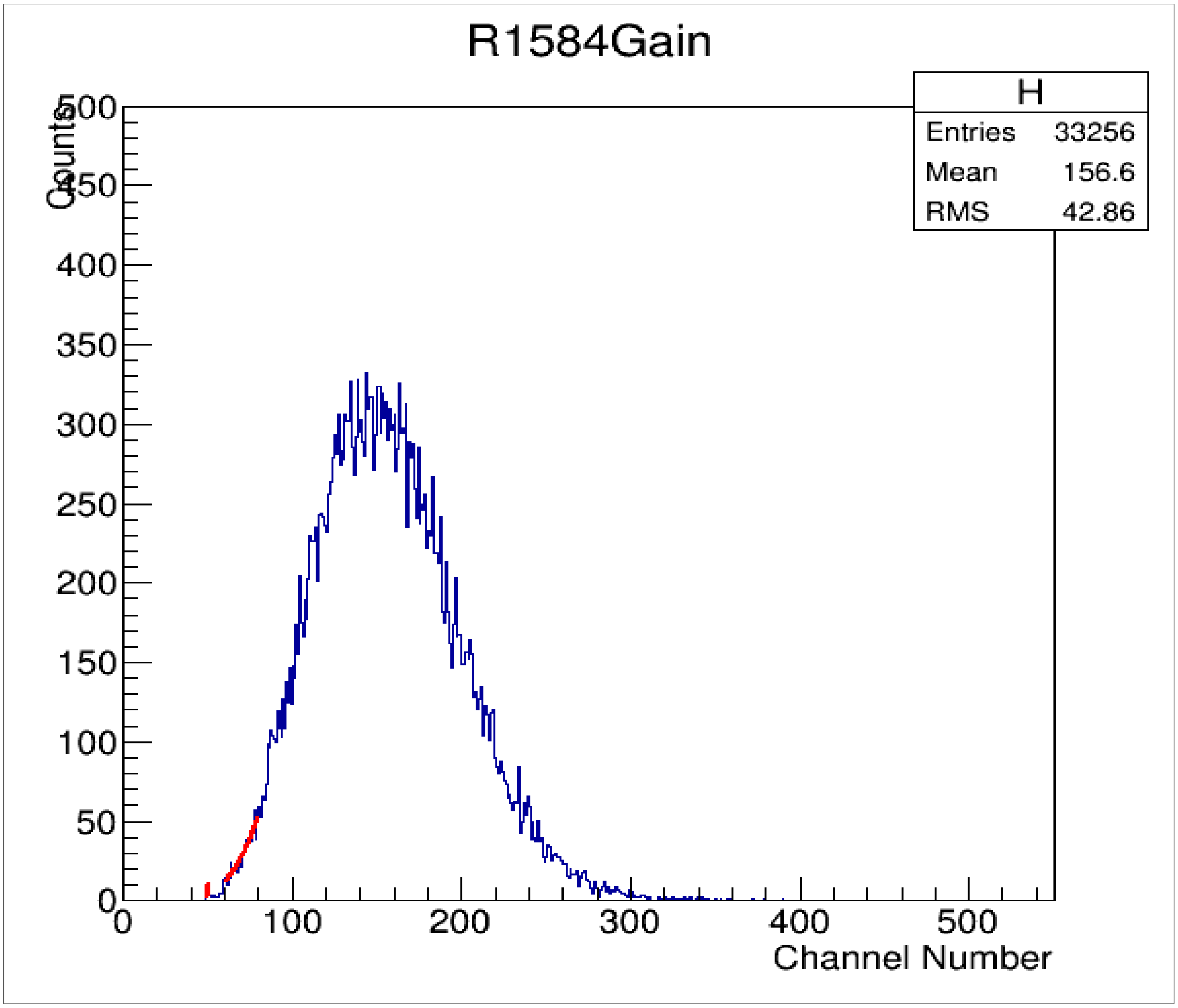

Figure 4: Signal received by the R1584 PMT with 3 aerogel tiles with a refractive index of 1.015 using 470nm light. This is one of the tests used to calculate the transmittance from received intensity.

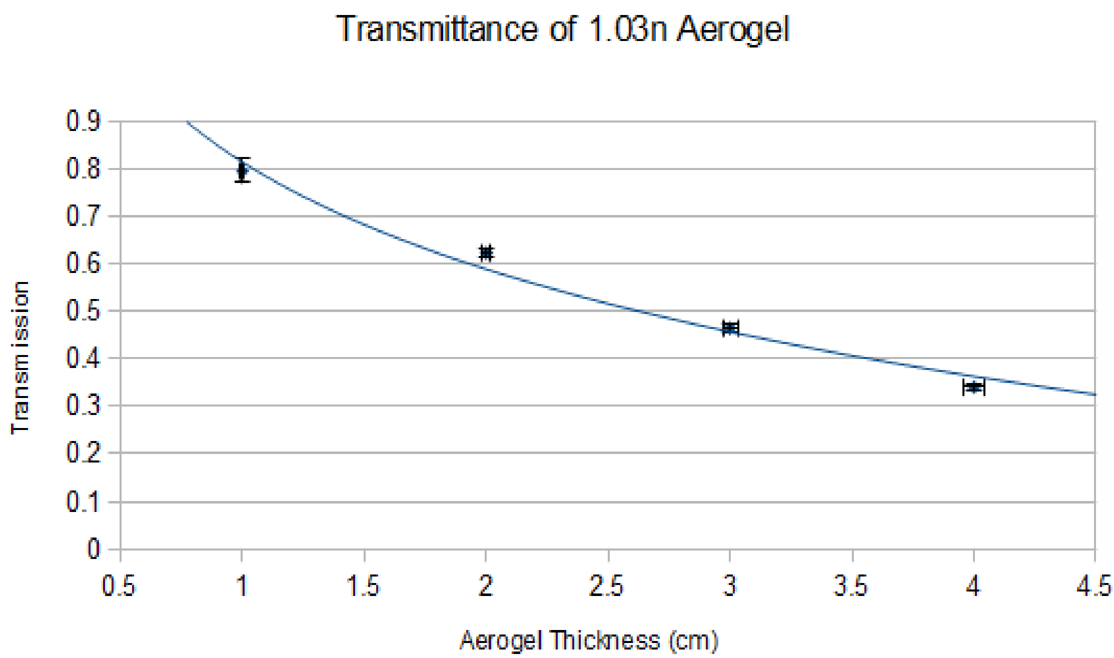

Figure 5: Transmittance of Aerogel with a refractive index of 1.03 with 470nm light.

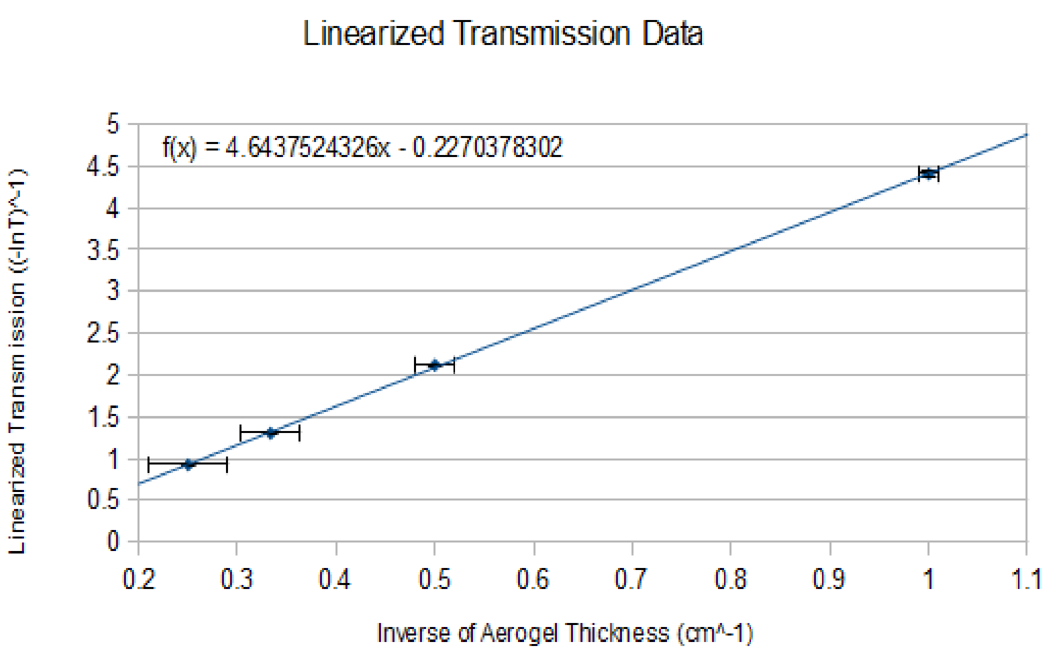

Figure 6: Linearized Transmittance of Aerogel with a refractive index of 1.03. The attenuation length is the inverse of the slope.

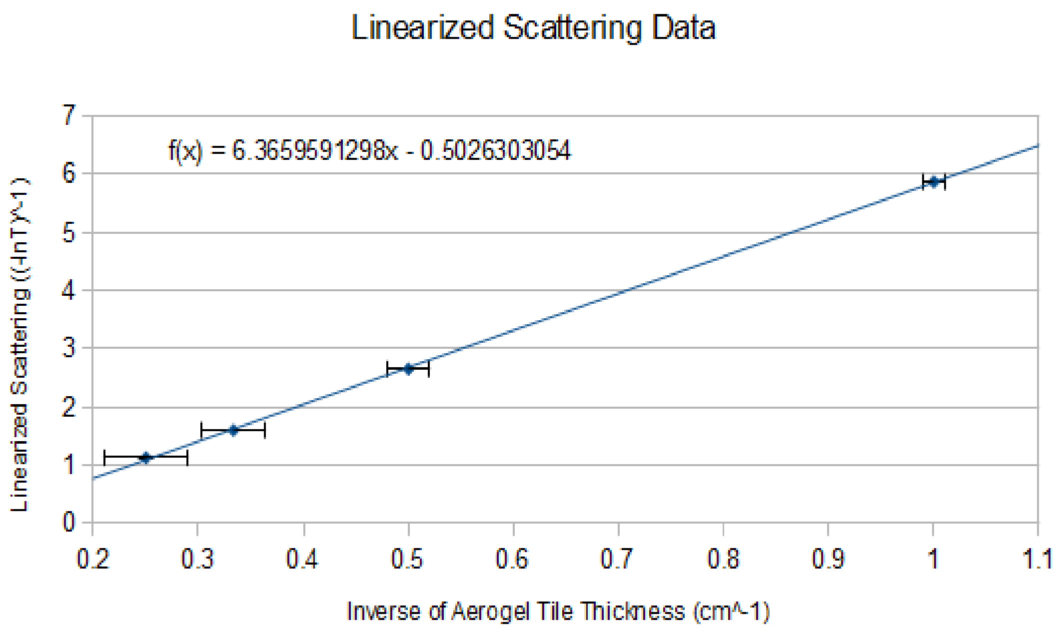

Figure 7: Linearized scattering data of 470nm light through 1.03n aerogel. This was calculated by accounting for the effect of absorption in the transmittance data.

No data on absorption length has yet been taken on aerogel with refractive indicies other than 1.03. However, for the purposes of calculating an approximate scattering length, absorption length will be assumed to be proportional to aerogel density. During experimentation, four tiles of aerogel in cases labeled for 1.02n aerogel were tested. However, one of these cases had been mislabeled, and only two of the tiles had a refractive index of 1.02. While the data taken does not represent aerogel with a refractive index of 1.02, it is still useful in gauging a trend. The density of aerogel in this case was assumed to be the average of the density of 1.03n and 1.02n aerogel.

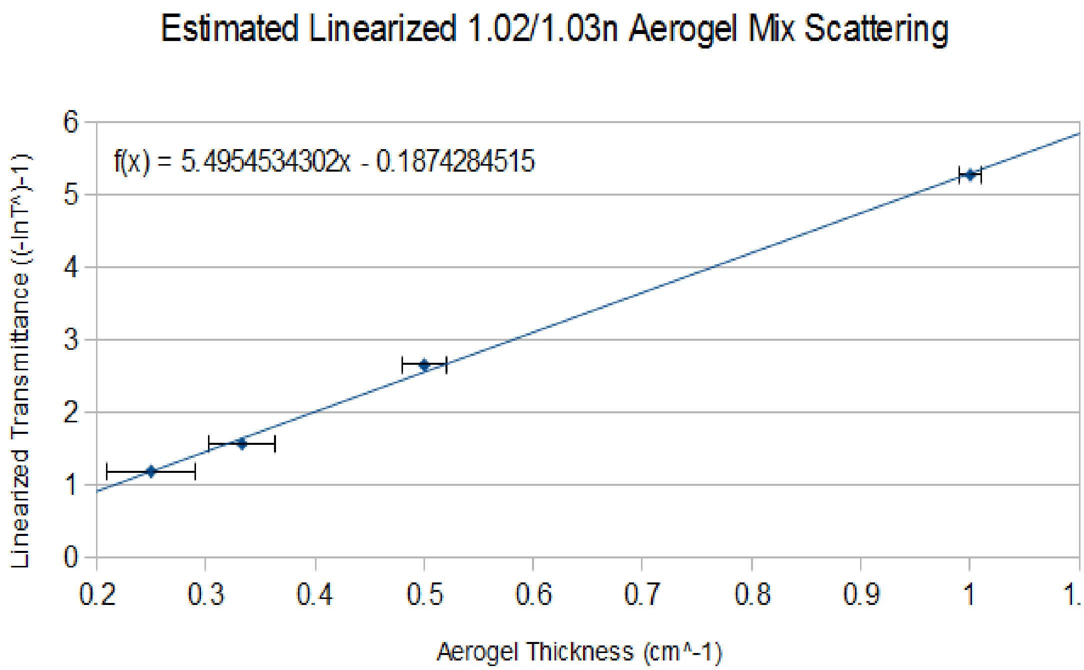

Figure 8: Linearized scattering of 470nm light though a mix of 1.03n and 1.02n aerogel tiles. This was calculated assuming a liner relationship between aerogel density, which is related to refractive index, and aerogel absorption length. The values used to calculate this are rough approximations, and while the slope of this graph represents an approximate scattering length, it is a rough approximation and only included to show a general trend.

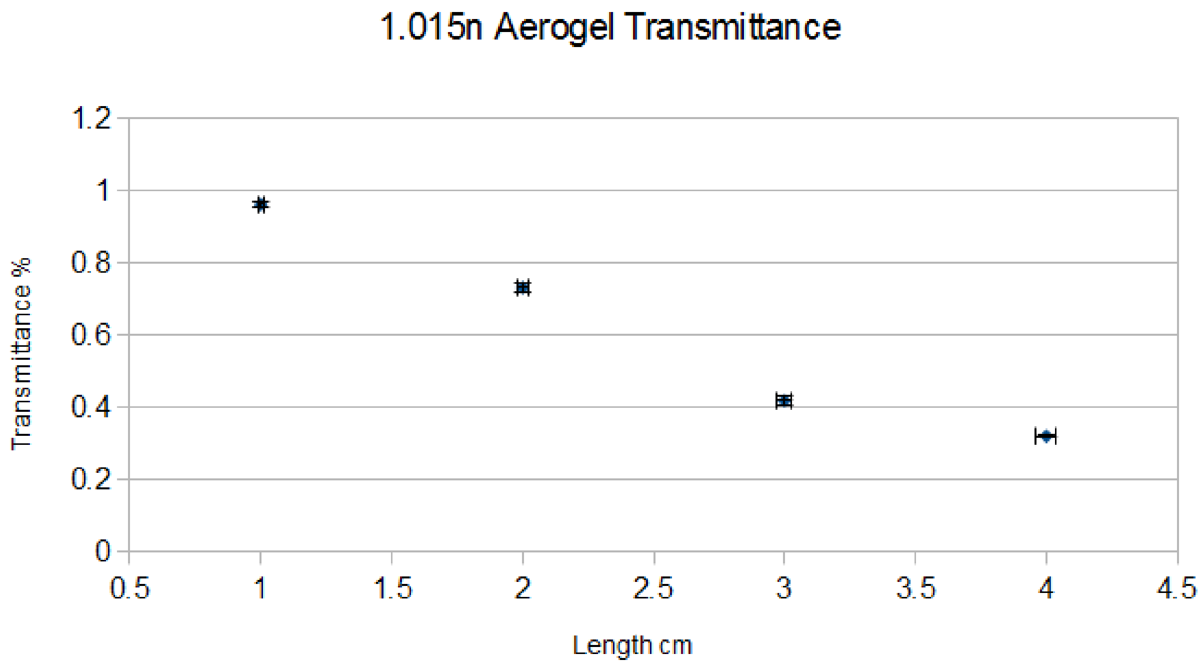

Figure 8: Transmittance of 470nm light through 1.015n aerogel tiles.

This data was striking. It was the first to not fit some sort of exponential curve. If you attempt to fit one, the first two points would cause the y-intercept of the exponential to be greater than 1, and thus it would not be an accurate representation of the physical situation occurring, implying that with zero tiles, more than 100% of the light shining from the LED was reaching the PMT. This might imply that excess light somehow did reach the PMT. However, there was no change made to the experimental setup before this data was taken.. Additionally, the latter two data points could possibly fit on the line of an exponential decay equation, which suggests that there was either no error with the testing apparatus at all, or that the error was later corrected. This could also imply that the scattering of light in low-refractive index areogel does not follow a typical exponential decay pattern, and instead follows some other trend, at least at short thicknesses of aerogel. If linearization of this data is attempted by the same method as those used previously, there is not a linear slope to the graph between all the points. Treating each point on the graph separately, calculating attenuation length for each point yields the following results:

Number of Tiles	1	2	3	4
Attenuation Length (cm)	25.93 +-7.10	6.39 +-.37	3.43 +-.12	3.50 +-.01

When calculating absorption assuming linear relationships between density, refractive index, and absorption length, the first data point gives an impossible result: a negative absorption length and a transmittance greater than 100%. Thus that point of data will be ignored. A rough estimation of scattering length is as follows:

Number of tiles	2	3	4
Scattering Length (cm)	9.2	4.1	4.2

The scattering length and approximate scattering lengths of 470nm light through aerogel of varying refractive indies is as follows:

Refractive Index	Scattering Length
1.03	6.37cm +-.28cm
1.03/1.02 mix	~5.45
1.015 (at 3 and 4cm)	~4.2

Data Analysis:

The main quality shown by this data is that as refractive index decreases, so does scattering length. This is most likely due to changes in the size and distribution of pores in the aerogel material as refractive index varies. At lower refractive indices the density of the aerogel is also much lower, meaning that there is significantly less silica as refractive index decreases. Because of this, there are far more pores large enough to cause Rayleigh scattering. This is the most probable explanation for the decrease in scattering length as refractive index decreases. While tiles of refractive index 1.02 were not tested in isolation, they still seem to follow this trend. The 1.015n tiles also seem to follow this trend at larger thicknesses.

The 1.015n aerogel unlike all the others seemed to defy the exponential pattern, at least at low thicknesses. This may be because of unique properties of the aerogel, or some fault in the testing methods. If light tends to scatter in different angles in different refractive indices of aerogel, it may have been possible for some light to scatter and still make its way through the aperture, which could be corrected using a different aperture. At larger thicknesses the influence of this would decrease as the possible angles at which light could scatter and still pass through the aperture would significantly decrease, even with the possibility of multiple scatterings.

Future Research:

In the future, it would be beneficial to measure an exact absorption length for aerogel of refractive indices other than 1.03, which would in addition to being useful in its own right add value to the data collected through this experiment. Additionally, especially due to the Rayleigh scattering nature of aerogel, it would be beneficial to study scattering and absorption at different wavelengths of light, such as longer wavelength ultraviolet through the visible spectrum. Additionally, a better aperture could possibly be designed to see if that had any effect on the 1.015n aerogel data.

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