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Determination of Alpha Radiation-Induced Fluorescence Efficiency

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By

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Abstract

This work was conducted to develop a method for obtaining stable and reproducible photon count yields to be used in calculating a reliable value for alpha radiation-induced fluorescence efficiency in air. The basis for this experiment was the knowledge that alpha radiation causes the nitrogen in the earth's atmosphere to fluoresce. Developing a fluorescence efficiency for alpha radiation is to quantify how efficiently the energy from alpha radiation causes nitrogen to emit photons in air. The experiment was conducted using highly controlled atmospheres of both air and nitrogen. This allowed for the experiment to determine how efficiently alpha radiation was able to induce fluorescence in air and in nitrogen. An air fluorescence efficiency and a nitrogen fluorescence efficiency was calculated in this experiment. The stable and reproducible data seen in this experiment shows that the experimental method developed is the most reliable method developed to date to determine alpha radiation-induced fluorescence efficiency.

Chapter 1

Problem Statement

The area of alpha particle (α) induced air fluorescence efficiency has not been well documented or studied previously [1]. Conversely, the amount of information available on beta induced air fluorescence efficiency provides detailed experimental procedures, reliable experimental results, and accepted values for beta-induced efficiencies and photon yields. This has primarily come about through the study of ultra-high energy cosmic rays (UHECR). The intended purpose of this experiment is to work towards developing reliable and experimentally sound $\alpha - particle$ fluorescence efficiency and photon yield measurements.

An $\alpha - particle$, when resulting from radioactive alpha decay, has a low penetration and can be stopped by passing through a few centimeters of air or solid materials more than a few micrometers in depth. The makeup of an α is identical to that of a helium nucleus, because it contains two protons and two neutrons. $\alpha - particles$ found in cosmic rays are at a much higher energy than those produced by radioactive decay and helium nuclei form ten to twelve percent of cosmic rays. Consequently, this higher energy results in $\alpha - particles$ gaining the ability to penetrate the skin layer and thicker structures.

The development of methods to detect $\alpha - particles$ in air will be aided by advances in the quality and reliability of $\alpha - particle$ air fluorescence efficiencies and photon yields. The first step that will be taken to accomplish this and the bulk of my experimental work was investigating and developing a sound radiometric method for collecting fluorescence via a photomultiplier tube and a spectrometer and testing the reliability of the data. We attempted to use a NIST traceable spectrometer with an irradiance calibration to establish the absolute intensity of air fluorescence emissions. The goal was to be able to determine the final intensity of fluorescence present when optical components that subtract from the initial intensity of the fluorescence are present in the light path. By knowing the final intensity of emission from a calibration source (such as the deuterium lamp used here) and taking into account the effect each component of the optical setup had on the amount of the lamp emission that passed through the system, the calibration of the system can be completed. A system that has been calibrated allows an unknown intensity of alpha-induced fluorescence to be quantified by using the calibrated ratio between the initial and final optical signals. The intensity of light processed for data will then be known without taking into account each component in the system separately per fluorescence source.

Chapter 2

Literature Review

§2.1 α fluorescence efficiency and detection

Alpha induced ultraviolet (UV) air fluorescence is mainly emitted by molecular nitrogen which is the largest percentage component of gas in the air. With this in mind scientists have gone on to study the fluorescence caused by various radiation sources in both air and pure nitrogen gas. Alpha emitting radiation sources are typically hard to detect due to the fact that alpha particles only travel a few centimeters in air [2]. The $\alpha - particles$ travel shorter distances in air, and transfer more energy from the particle to the air per distance travelled when generating fluorescence. The motivation given by Bachelor et al. [1] for conducting research on the alpha-induced atmospheric nitrogen fluorescence yield is to be able to detect contamination to the environment. Since alpha radiation makes up part of UHECR nitrogen fluorescence can also be used to detect the UHECR. Current methods to detect alpha radiation contamination in the environment require the person operating a conventional radiation detector to be within a few centimeters of the contamination. This is due to the fact that alpha particles only travel a few centimeters in air. The potential for quantification of contamination by its fluorescence requires, among other things, the specific type of radiation quantum fluorescence efficiency. This fluorescence efficiency is the ratio of the radiation energy emitted from the source to the energy produced in ultraviolet photons. Bachelor et al. claims to have determined the air fluorescence efficiency of alpha particles in air generated by Americium 241 (^{241}Am) sources of alpha radiation [1]. However, in the experiment conducted by Bachelor et al. there were no atmospheric controls in place and they have acknowledged that their experiment involved a high degree of uncertainty.

The experiment conducted by Bachelor et al. treated the fluorescence efficiency as a free parameter in their physical model of the experiment. Approximately ten measurements were taken and a best fit of the results was applied. The best fit of the alpha particle fluorescence efficiency at the peak of their optical emissions was 1.3×10^{-5} about thirty-eight percent smaller than a previously reported by Bachelor et al. They estimated that the total uncertainty on their results for the ^{241}Am source was approximately twenty percent [1]. The papers mentioned in this section are the only few that provide values for alpha induced fluorescence efficiency. When compared to the dozens of papers produced on beta induced fluorescence efficiency [5, and references therein], the lack of information on the alpha efficiency is starkly apparent. The main radiation source that cosmologists study to quantify UHECR is beta radiation and the literature available gives reliable numbers from experiments conducted with controlled atmospheres [5].

§2.2 β-induced fluorescence efficiency studied in detail

The detection of air fluorescence is used in the case of beta radiation as well to detect UHECR and determine cosmic ray energy. The atmospheric fluorescence may be measured from the trajectory of an extensive air fluorescence shower created by an UHECR. This type of experiment utilizes photon yield (the number of photons produced by electrons per meter of travel) from electrons exciting air of various temperatures and densities as the most fundamental information for estimating the primary energy of UHECR [3].

Another motivator for developing air fluorescence yields is achieving a reliable energy calibration of fluorescence telescopes. This need has promoted a number of experiments for the measurement of this parameter in the nitrogen fluorescence wavelength interval (~300-400nm) [4]. Nagano et al. [3] published measurements of the fluorescence yield using electrons from the beta decay of a Strontium 90 (Sr 90) radioactive source (average energy 0.85MeV). Waldenmaier et al. [5] goes into detail in his experiment about the different atmospheric conditions the experiments were conducted under and how the variation affected the efficiencies and different yields being observed. The pressure of the atmosphere, the density of the air and the gaseous makeup of the air all affect the values.

Nagano et al. have provided equations that were used to calculate the photon yields and the fluorescence efficiencies. The equations when used with alpha radiation sources will have to be altered and modified slightly, but an understanding of the physical parameters that affect the fluorescence efficiency and the photon fluorescence yield can be garnered from this previous work. The changes that need to be made to the equations reflect the reasons why the common argument for the interchangeability of beta and alpha efficiencies does not hold in experimentation. Bachelor et al. state that their estimate of the α fluorescence yield is at least 38% smaller than β-induced fluorescence measurement [1].

Chapter 3

Methodology

The experiment will be based on creating a calibrated optical measurement system to be used in experiments pertaining to the determination of alpha radiation induced fluorescence efficiency. In the initial experiment we will be using a National Institute of Standards and Technology (NIST) traceable spectrometer as the basis for creating a calibrated optical system that will be reliable for radiometric purposes. A light source will provide a known amount of light intensity into a light filtering and detection system. The percent of emitted light that enters the system depends on the numerical aperture (NA) of the collection system. After entering the light is affected in various ways by the optical components in its path. The way in which each element affects the fluorescence will be known before it is put into the system. Light of a diminished intensity will then be focused on the spectrometer, which will then pass the spectrum of the fluorescence to a detector. The final intensity that the detector reads can be correlated with the initial light intensity by taking into account the specifications of each optical instrument and tool in the system. By knowing the ratio of incoming fluorescence to the amount of detected fluorescence the readings that the detector makes gains an experimental significance by providing the transmission efficiency of the system.

§3.1 Light Source and Collection

A NIST traceable light source emits a known amount of light intensity. In other words it emits a known amount of energy in the form of photons. A photon (γ) has a quantized energy that can be found by knowing either its wavelength (λ, unit nm) or frequency (*f*, unit 1/s).

$$\boldsymbol{\gamma = hf = \frac{hc}{\lambda}}$$

$$(\boldsymbol{h = Plank's\ constant = 6.626068 \times 10^{-34}\frac{m^2kg}{s}})$$

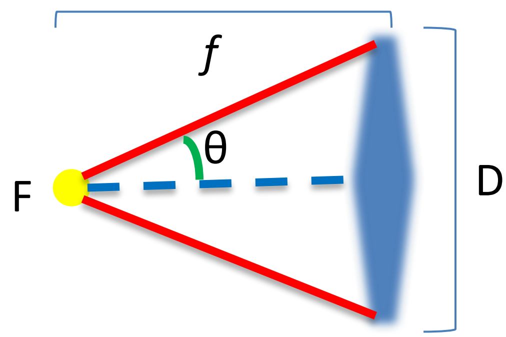
NIST establishes the metrological traceability of results obtained by customers with a NIST calibration and measurement certificate for a specific instrument. NIST provides traceability to conform to the most recent definition of metrological traceability provided in the *International Vocabulary of Metrology*: "Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."

Once light emission occurs from the calibration light source it can be collected by the collection lens. Each collection lens has a certain focal length that optimizes its ability to collect fluorescence. Each objective has a known numerical aperture: a dimensionless number that characterizes the range of angles over which the lens can collect light. A numerical aperture is normally calculated using the index of refraction (*n*) of the medium through which the lens is operating and the half-angle (θ) of the max cone of light that can enter or exit the lens.

$$NA = n\sin(\theta)$$

When a lens has a larger numerical aperture, it will collect more light and provide a brighter image, but less depth of field. Often the quantity in question or known is the f-number of a lens (*f/#* , *N)* which expresses the angular aperture of the lens and is the ratio of the focal length (*f*) to the diameter (*D*) of the lens.

$$N = f/D$$



The f-number can be approximated using the numerical aperture and assuming the index of refraction in air (n=1).

$$N \approx \frac{1}{2NA}$$

§3.2 Optical System

Once the fluorescence has been collected it will be passed through a specifically designed optical system. Part of the experiment is to create a system that will pass on the highest quality and correct quantity of fluorescence. Each element within the system from a clear lens to a light filter will affect the amount and wavelength of light that will pass through the system. This experiment was conducted in an effort to work towards the development of an alpha radiation induced fluorescence efficiency. Our system was designed to optimize the collection of wavelengths from fluorescence created through excitation by alpha radiation.

An example of a gas that fluoresces from excitation by alpha radiation is nitrogen gas. This gas emits fluorescence at wavelengths typically in the range of 300 to400nm. As a further example a system set up to collect this light would have filters in place to hinder the passing of light outside this range, but they would also have an effect, although a slighter one, on the amount of fluorescence within this range that is passed through. That amount will need to be accounted for on an individual basis in the calibration of the system. Once calibrated the number of photons present at the beginning of a certain experiment will be determined directly from the final amount by utilizing the known calibration ratio of incoming photons to detected photons.

§3.3 Spectrometer and Detector

The last two steps in the system calibration will be taken by a spectrometer and a detector. A spectrometer will typically use wavelength (λ), frequency (*f*), or energy (E, unit eV) to measure a specific property of the fluorescence. The most common property measured is the intensity of the light. Spectrometers take in light and measure the wavelength and intensity, which can then be used in calculations and observations. Spectrometers work by directing light from an input slit onto a grating. The grating diffracts the light into various angles based on its wavelength or frequency into a spectrum and directs that fluorescence to a detector.

Readings taken by optical detectors are understood by knowing the quantum efficiency (Q_e) specific to the device being used in each experiment. A Q_e varies between different types of devices and also between devices of the same type and make. Each individual device comes with a Q_e specific to it. The company that manufactures these devices must send out specific Q_e test sheets along with the device in order for the detector to be used accurately. The Q_e is basically an accurate measurement of a device's electrical sensitivity to light and is often characterized for a particular device at each photon energy by taking measurements over a range of wavelengths.

The Q_e is needed to understand the data that a detector provides. An optical detector often outputs data in the form of counts. A count, often called the electron count, is the measurement of the amount of current per sensor area per unit time and can be used to determine the number of photons that have hit the sensor. Since the sensor has a known Q_e the number of electrons can be converted into photons. A Q_e is the ratio of the number of photons that hit the sensor per second to the number of current pulses per second that the device outputs.

$$Q_e = \frac{electron/sec}{photon/sec} = \frac{current/(charge\ of\ one\ electron)}{(total\ power\ of\ photons)/(energy\ of\ a\ photon)}$$

At the end of optical system we will read a number of electrons (count) from the detector. That number can be converted into a number of photons so that the ratio between the beginning photon count and the final photon count can be determined. In that same way the initial and final energies can be compared for the light source.

§3.4 Applications for Developing Alpha Efficiency

A calibrated system can be used for the detection and characterization of fluorescence induced by alpha radiation. The alpha particles can then provide excitation energy to the gas and the gas emits fluorescence. For calibration light is collected by a lens and passed through the optical system. Our system directs the calibration light into a spectrometer that will divide the light into a spectrum based on its wavelength. Next the detector converts the photons that hit per surface area per unit time into an electric current. The number of counts can be converted into the number of photons that hit the surface per unit time or the total intensity of the light. If completed successfully, at this stage of the experiment the calibration of the system with the known NIST traceable spectrometer will have been completed and a ratio between the initial photon count and the final photon count will be known. The detected number of photons created in the alpha experiment will be compared to the ratio developed in the calibration experiment. This step will provide us with the initial number of photons or the initial amount of fluorescence energy that the alpha radiation produced. The alpha radiation deposited a certain amount of energy to cause the gas to fluoresce and the amount of energy contained in that fluorescence is now known through radiometry. Another ratio will then be made by comparing the energy input (alpha radiation energy) to the energy output (gas fluorescence energy) and this ratio will be the efficiency of alpha radiation for inducing fluorescence.

Chapter 4

Theory and Equations

To help in understanding the components of the final equation that will be used to determine the fluorescence efficiency (f_e) of alpha particles, the equation will be broken down into two separate equations. The two equations will be presented and their components will be discussed in detail to provide a thorough understanding of the experiment. Some of the components of the equations are well known and require no experimental data to be determined. Other factors are completely determined from experimentation.

Equation 1.

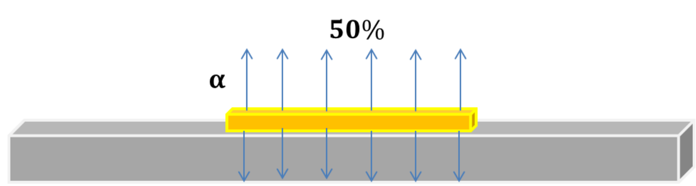
$$N_\gamma = \frac{N_\alpha E_\alpha f_e}{E_\gamma}$$

Equation one is used to determine the total number of ultra violet (UV) photons generated by the alpha radiation, N_γ. Now an investigation into each component of equation one must be completed in order to determine which of them needs to be confirmed through experimentation prior to the main experiment. Many of the components will not need any preliminary experimentation. Those will be able to be determined through use of provided manufacturer's specifications or well-known physical laws.

The first component of the equation N_α is the number of $\alpha - particles$ an alpha radiation source will emit per second. In this experiment an Americium 241 radiation source will be used. The equation to determine N_α:

$$N_\alpha = A\ (3.7 \times 10^{10}) \frac{\frac{decays}{sec}}{Ci}\ (0.5)$$

The activity, A, of a radioactive source is the number of decays per unit time that the source undergoes. Activity is measured in a unit known as a curie, Ci. The curie is a non-SI unit that measures radioactivity and has the value of $3.7 \times 10^{10} \frac{decays}{s}$. In the above equation this conversion is present to convert the activity provided by the manufacturer in curies to the number of decays happening per second. This is important because the number of decays per second is equal to the number of alpha particles generated by the source per second. The decrease by 50% that is seen at the end of the equation is due to an estimate provided by the manufacturer. They estimate that only half of the particles are emitted from the thin gold foil encasing the source in a direction that can be read by the detector. The estimate is due to the fact that roughly half of the $\alpha - particles$ are emitted up and roughly half are emitted down into the metal holding the source in place. Due to the estimated 50% the final determined value of N_α is relatively uncertain. The activity of the ^{241}Am source is given in the product description.



The second term E_α, which is the approximate energy of the $\alpha - particles$ emitted from the source. The exploration into this term is simplified by the fact that the manufacturer has provided the value for this term. An ^{241}Am source has an original energy of approximately 5.4 MeV. However, due to collisions in the foil containing the ^{241}Am isotopes the manufacturer has specified that the average alpha energy is approximately 4.8 MeV. An MeV is a unit of measurement used in physics known as a mega electron volt and an electron volt for reference is equal to $1.602 \times 10^{-19} joules$. When the first two terms of equation one are taken together, they give the power emitted as radiation from the source.

Most important for this experiment is the third term. It is the fraction of $N_\alpha E_\alpha$ (radiated energy or power) that gets turned into UV photons, f_e. This fraction is also known as the fluorescence efficiency of alpha particles. It quantifies how efficiently the energy emitted from the alpha source is converted into UV fluorescence energy. This experiment seeks to discover this value through experimentation and careful examination of all factors involved.

Finally in equation one we have the fourth term in the denominator of the equation, E_γ. It is the energy of a photon at the fluorescence wavelength in the UV range. This wavelength is due to the particular electronic structure of the N_2 molecule emitting the fluorescence. N_2 emits photons most efficiently at a wavelength of 337nm and the experiment will be conducted with this in mind. The energy of a 337nm photon can be determined through the relation of energy and wavelength:

$$E_\gamma = \frac{hc}{\lambda}$$

$$h = plank'sconstant = 4.136\ \times 10^{-15} eV \cdot s, \qquad c = speed\ of\ light = 3.0 \times 10 \frac{m}{s},$$

$$\lambda = wavelength = 337nm$$

For photons at 337nm the energy is 3.68eV.

Equation one provides the number of photons expected to be emitted from a source in a random spherical distribution per second. This equation alone would be sufficient given the quantum efficiency, Q_e, of the detector if the detector could detect the whole spherical distribution of the signal. This is not possible in any physically realizable experimental setup. This experiment will use a photomultiplier tube (PMT) light detector with a face of radius 12.5mm, which will only be struck by a fraction of the total fluorescence emitted spherically. Equation two will take on the job of tailoring equation one to fit into the experimental parameters.

Equation 2.

$$N_c = Q_e N_{\gamma p}$$

Equation two determines the number of counts that the detector, in this experiment the PMT, will register from a spherical distribution of photons when the quantum efficiency of the device is known and the number of UV photons hitting the PMT per second, $N_{\gamma p}$, has been determined. Equation one and equation two are connected through the term $N_{\gamma p}$:

$$N_{\gamma p} = N_\gamma \left(\frac{A_{PMT}}{4\pi {r_{sphere}}^2}\right)(T_w)(T_f)$$

The first term in the equation for $N_{\gamma p}$ is the same term provided by equation one. Next is a purely geometrical term that can be determined through careful measurements of the areas and distances involved in the experiment. A_{PMT} represents the area of the PMT face and in this experiment is the area of a circle with radius 12.5mm. When the area of the PMT face is divided by the total spherical surface area at the distance of the PMT from the source, the fluorescence fraction of the distribution that the PMT actually detects can be determined. The area of the spherical distribution is determined by measuring the distance from the PMT face the source of the fluorescence. That distance is the spherical radius of the distribution. In the case of this experiment r_{sphere} is 368mm (~14.5").

When these areas are divided by one another the fraction of photons hitting the PMT per second is determined when combined with the N_{γ} term.

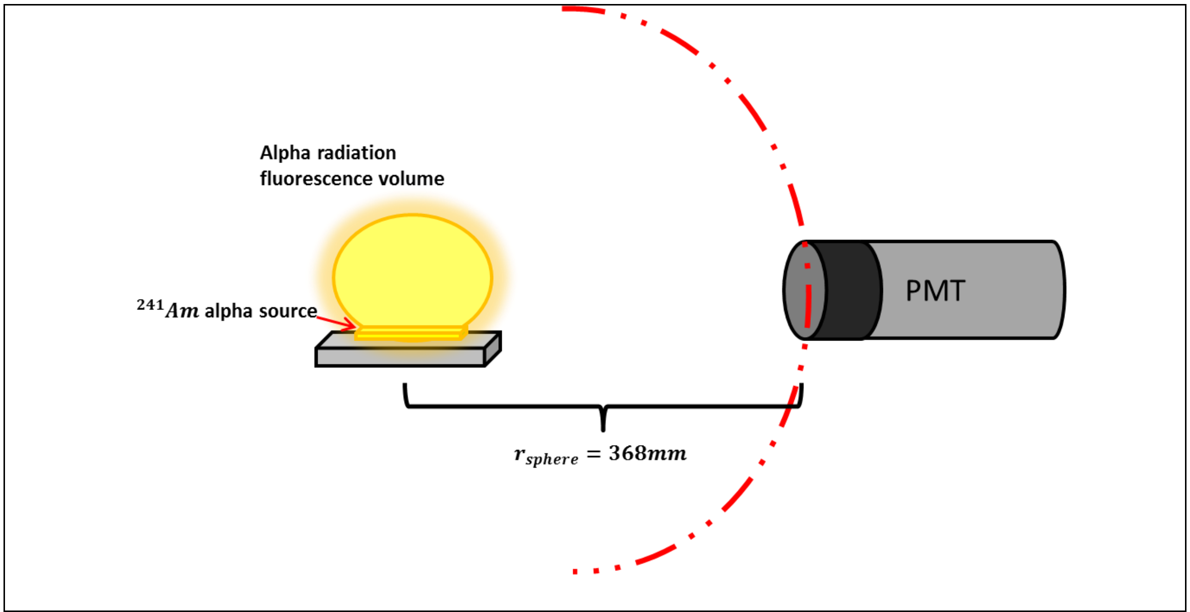


Figure 1. Spherical radius

The next two components in the equation for $N_{\gamma p}$ are experimentally determined transmission percentages. Fluorescence from the source must pass through the port window of the vacuum chamber containing the source and through a filter that transmits photons in a small band around 337nm. Each of these optical components decrease the total amount of fluorescence detected at the PMT face. These two factors are determined through an experimental procedure that will be described in the next chapter. The percent transmission of all the fluorescence through the port window is roughly equal to 92%. However, the percent transmission of just the 337nm photons through the 337nm filter is approximately 28%. Each of these factors must be taken into account to accurately determine the correct fraction of the total spherical distribution of the fluorescence that reaches the PMT.

Now that the second term of equation two has been explored what about the first? The first term in the equation is the quantum efficiency of the detector being used. The quantum efficiency of a detector is defined as the percentage of photons that hit the detector and produce an output count. It is a measurement of the detectors sensitivity to light electrically. When the number of counts, N_c, is divided by the quantum efficiency, Q_e, the number of actual photons hitting the PMT face can be determined.

One preliminary step of the experiment that will be explored in the next chapter is determining the quantum efficiency of the PMT using the NIST traceable spectrometer. Sadly, this step of the experiment met with some difficulties due the differences in sensitivity of each of the detectors. The final calculation of the fluorescence efficiency will be accomplished using the quantum efficiency that the manufacturer has provided as the approximate quantum efficiency of the PMT at 337nm. This inability to more precisely measure the quantum efficiency of the PMT will be a source of error in the final calculation.

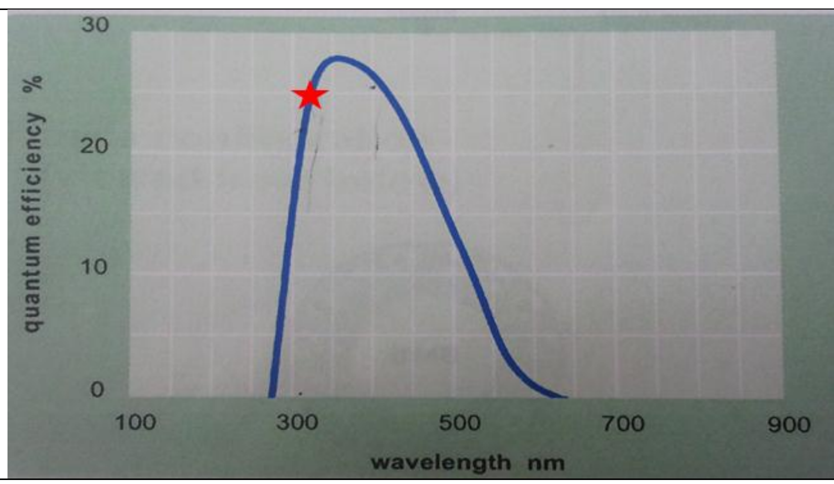


Figure 2. Quantum Efficiency Curve

Finally, since all components of both equations one and two have been explored they can be combined in a meaningful way to determine the fluorescence efficiency of alpha-induced radiation from the Americium-241 source.

Equation 3.

$$f_e = \frac{N_c E_\gamma 4\pi r_{sphere}^2}{Q_e N_\alpha E_\alpha T_w T_f A_{PMT}} \text{ , } Fluorescence\ Efficiency$$

N_c has been measured and will be used to determine f_e.

Chapter 5

Experiment

§5.1 Point Source

Light sources that emit light in such a manner that the fluorescence at a distance r from the source falls off in a $\frac{1}{r^2}$ pattern as the distance increases are known as point sources. When the light being emitted by a point source is seen at the desired distance, the spectrometer or PMT collecting that signal will view it as only a portion of a source emitting light in all directions. This experiment was expected to approximate point optical sources in both the calibration stage and the data taking stage.

The first step taken in this experiment was to take a NIST traceable spectrometer and determine if the deuterium light source used for calibration would behave as a point source at the desired distance. In the main experiment the distance between the source and the detector is 14 ½ inches (~37 cm). To determine the $\frac{1}{r^2}$ drop-off of the light intensity at this distance the spectrometer was placed at distances less than, equal to, and greater than the target distance. The irradiance measurements taken at these distance were then plotted and the drop-off confirmed with a best fit curve. At the desired distance of 14 ½ inches the deuterium lamp used in calibration was determined to behave in such a manner as to be a reasonable approximation of a point source.   More importantly the curve dropped smoothly and was not highly sensitive to side to side (lateral) motion of the detector.

The importance of this experimental step comes from the fact that small shifts in alignment of the light source and detector may be forgiven in detection when the light source behaves in this manner. A small lateral shift in the alignment from one data run to the next is not expected to significantly affect the data results.

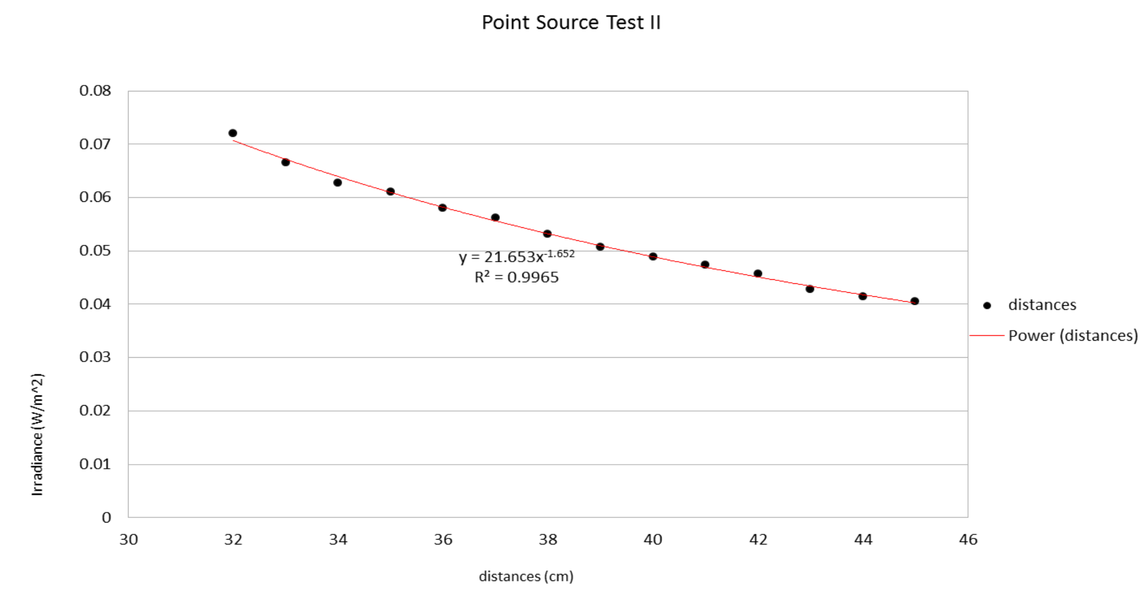


Figure 3. Point Source Test II

§5.2 Optics

To calibrate the amount of light that is ultimately reaching the face of the spectrometer and the PMT, measurements must be taken using a deuterium lamp light source with each optical component separately and together. This will allow the percent transmissions T_f and T_w to be developed for both the 337nm filter and the port window.

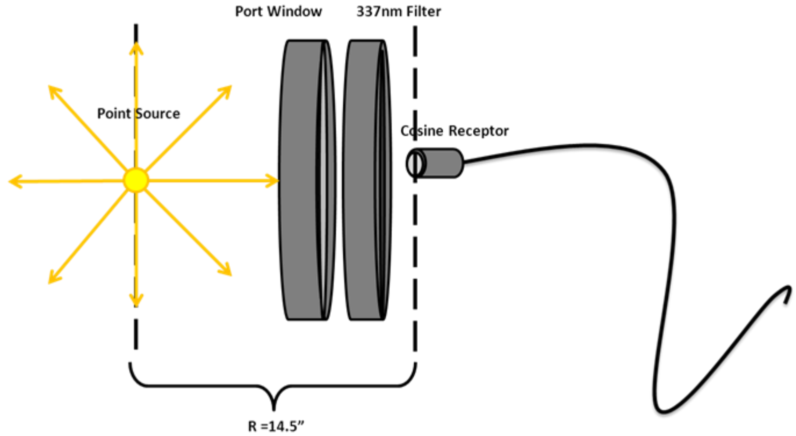


Figure 4. Optical Components

The test to determine the port window's percent transmission was accomplished by taking two sets of the measurements. The first set of measurements was taken with a cosine receptor and fiber coupler attached to the spectrometer at the approximate distance from the light source of the PMT in the main experiment. This measurement was taken without any obstructions in the way of the light. There were no surfaces in between the light source an the detector. This measurement was compared to the next measurement. The second measurement was accomplished by placing the port window into the optical setup at the approximate distance from the source and from the detector that it will occupy during the actual experiment. This distance is approximately 13 inches from the light source and 1 ½ inches from the detector. The irradiance measurement taken through the port at this distance was summed over all wavelengths and then divided by the first measurement summed over all wavelengths. This yielded the percent of all light being transmitted through the window to be 92%. This could be confirmed through a common rule for optics that each reflective surface, both faces of the window, reflects approximately 4% of the light passing through.

Next, to determine the percent transmission of the filter the lamp was placed in the vacuum chamber and aligned with the cosine recptor. The filter was then placed on the outside of the port window next to the chamber. Its placement in this test is the same as it is when the PMT is present. A set of light measurements was taken at this disatnce with the spectrometer taking a scan every 501ms and averaging eleven of these scans together. The filter was then removed and a measurement was taken in the same manner as when the filter was present. This was repeated five times for a total of five filtered measurements and five unfiltered measurements. The filtered measurements were then averaged together and the unfiltered measurements were also averaged together. The filtered average was then divided by the unfiltered average. The percent transmission at a wavelength of 337nm was determined to be approximately 28% from this step in the experiment.

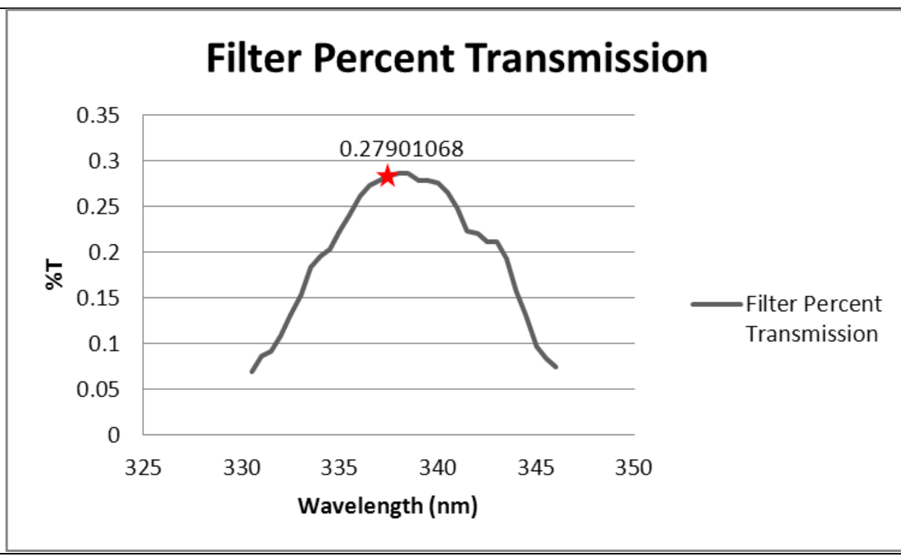


Figure 5. Filter Percent Transmission

§5.3 Quantum Efficiency

In an attempt to determine the quantum efficiency of the PMT before resorting to the manufacturer's specification, a test experiment was developed. The deuterium lamp was placed in the center of the chamber and aligned with the center of the PMT face. Between the PMT and the lamp the 337nm filter, the port window, and an additional neutral density filter were placed in the path of the light. Seven count readings from the PMT were then taken with the lamp on and the lamp off. The Lamp off measurements were to determine the dark count of the PMT. The actual counts from the light are the lamp-on PMT counts minus the lamp-off PMT counts. The additional nuteral density (ND) filter was placed in the path of light because of the sensitivity of the PMT detector. Without the ND filter, the extremely sensitive PMT was over stimulated by the light emitted from the lamp causing it to switch from reading counts to reading current. Our experiments are to be conducted using count readings. To be consitent, an ND filter was used to decrease the amount of light reaching the PMT from the lamp. However, this procedure necessitates another independent measurement of the ND filter transmission.

In order to know the quantum efficiency of the PMT, each optical component in the lamp's path must have a transmition percentage determined relative to the NIST traceable spectrometer. Each component has a certain percent transmission separately and together they have one singular percent transmision. Due to the low sensitivity of the spectrometer, measurements of the ND filter were taken outside using a more powerful light source: the sun. Several attempts were made to take a measurement of the sun's light with and without the ND filter. The spectrometer was too sensitive to take a reading without the filters. However, with the filters in place the spectrometer was not sensitive enough to take an accurate measurent above the background signal.

Due to the mismatch in sensitivities between the PMT and the spectrometer, developing an accurate quantum efficiency for the PMT was not possible with the spectrometer available for this experiment. Therefore, the quantum efficiency that will be used in the calculations will be the one provided by the manufacturer for the PMT.

§5.4 Photon Counting

In the main and final portion of the experiment, the Americium-241 alpha radiation source will be used in place of the lamp. To develop an efficiency for alpha-radiation induced air fluorescence, the source was placed in the center of a vacuum chamber.

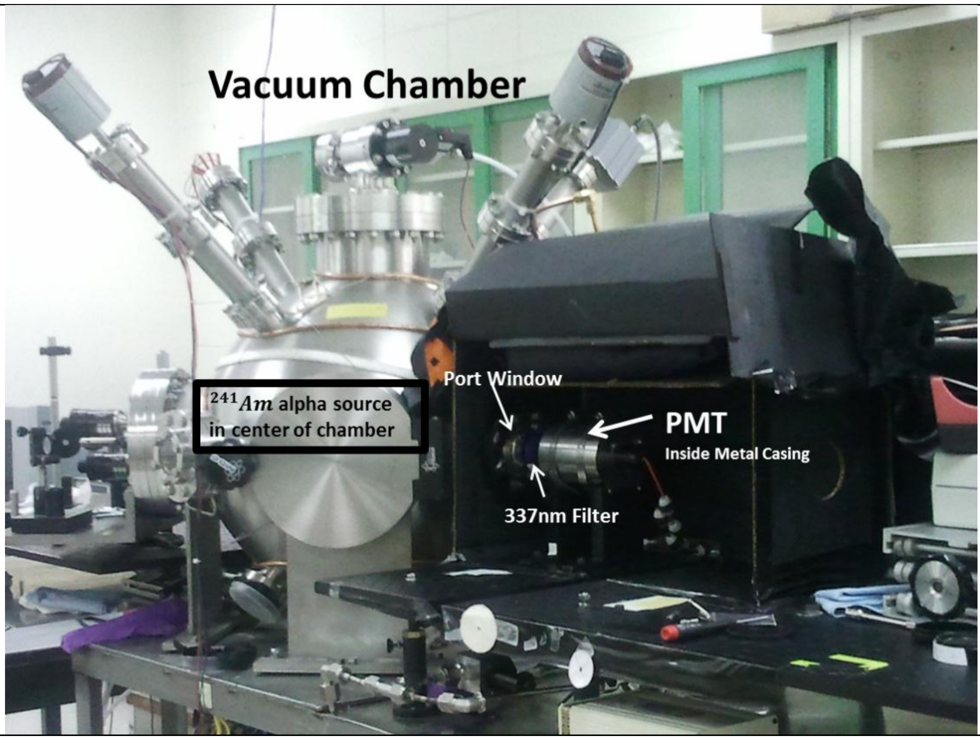


Figure 6. Experimental Apparatus

The chamber was then evacuated and then refilledwith dry air from a gas cylinder. The air was a 20.5% and approximately 79.5% mixture of N_2 and O_2 as analyzed by the manufacturer. Once the pressure in the chamber was raised using the dry air to approximately 740 torr, measurements of the flourescence in the chamber could be acquired. In the first set of data taken, seven readings of dark count were taken each over a ten second time period. The dark count readings were obtained using a remote contol slide to cover and uncover the source. All together seventy seconds of dark counts were measured. Next, the slide covering the source was moved and seven count measurements were taken of the fluorescence detected by the PMT from the source in air. The seven dark count measurements and the seven fluorescence count measurements were repeated three times. After the third set of measurements, the air was pumped out of the chamber and the chamber was then repopulated with air to a pressure of approximately 740 torr. The three sets of seven measurements were repeated and the chamber was again evacuated and refilled. A third final set of count readings were taken in the chamber of dry air for a total of sixty-three dark count measurements and sixty-three fluorescence measurements, with each count reading taken per ten seconds. Repeating the process with ultrahigh purity nitrogen ($UHP\ N_2$) results in sixty-three more dark count measurements and sixty-three fluorescence count measurements taken in the $UHP\ N_2$.

Chapter 6

<u>Data and Calculations</u>

§6.1 Data

The data tables below summarize the experimental count rate data (in counts per second) from the nine sets of dark count measurements obtained in dry air and $UHP\ N_2$ and the nine sets of fluorescence measurements obtained in dry air and $UHP\ N_2$. Each set consisted of seven 10-second measurements. Several runs of measurements were necessary to obtain in order to provide conclusive proof of the stability of the count measurements obtained. The reproducibility of the results is evident from significant quantity of highly stable data.

Dry Air Run A			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	6.9 +/- 1.3	24.8 +/- 1.9	17.9 ± 2.3
Set 2 Average Counts	6.4 +/- 1	24.9 +/- 1.7	18.6 ± 2.0
Set 3 Average Counts	7.2 +/- 1.4	25.0 +/- 1.4	17.8 ± 2.0
starting pressure 4.6E-6 torr,approx. run pressure 746 torr , averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 1			

Dry Air Run B			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	5.8 +/- 1	23.8 +/- 0.8	18.1 ± 1.3
Set 2 Average Counts	6.0 +/- 1.1	24.4 +/- 1.7	18.4 ± 2.0
Set 3 Average Counts	6.1 +/- 1.0	23.7 +/- 2.4	17.5 ± 2.6
starting pressure 4.7E-6 torr , approx. run pressure 743 torr, averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 2			

Dry Air Run C			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	10.2 +/- 1.4	27.0 +/- 1.4	16.8 $\pm$ 2.0
Set 2 Average Counts	10.9+/-0.8	27.9 +/- 1.2	17.0 $\pm$ 1.4
Set 3 Average Counts	11 +/- 1.2	26.8 +/- 1.0	15.8 $\pm$ 1.6
starting pressure 4.6E-6 torr , approx. run pressure 749 torr, averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 3			

Dry Air	
Run A	18.1 $\pm$ 2.1
Run B	18.0 $\pm$ 2.0
Run C	16.5 $\pm$1.7
$\boldsymbol{N_{c_{Air}} = Air\ Average}$	17.5 $\pm$ 1.9
Total dry air count average over 630 seconds	
Table 4.	

$UHP\ N_2$ Run A			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	10.1 +/- 1.2	143.4 +/- 2.4	133.3 ± 2.7
Set 2 Average Counts	10.5 +/- 1.4	144.2 +/- 1.7	133.7 ± 2.2
Set 3 Average Counts	10.5 +/- 0.6	144.4 +/- 4.3	133.8 ± 4.3
starting pressure 2.2E-6 torr, approx. run pressure 744 torr, averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 5.			

$UHP\ N_2$ Run B			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	10.2 +/- 1.1	147.0 +/- 2.3	136.7 ± 2.5
Set 2 Average Counts	10.3 +/- 1.5	144.5 +/- 5.0	134.2 ± 5.2
Set 3 Average Counts	9.3 +/- 0.6	144.8 +/- 5.8	134.5 ± 5.8
starting pressure 4.5E-6, approx. run pressure740 torr , averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 6.			

$UHP\ N_2$ Run C			
	Dark	Fluorescence + Dark	Fluorescence
Set 1 Average Counts	9.0 +/- 1.1	143.3 +/- 3.4	134.3 ± 3.6
Set 2 Average Counts	10.2 +/- 1.4	144.1 +/- 4.5	133.8 ± 4.7
Set 3 Average Counts	10.1 +/- 1.8	145.0 +/- 4.8	134.9 ± 5.1
starting pressure 4.4E-6 torr ,approx. run pressure 746 torr, averages are of 7 10 second count measurements, uncertainties in experimental count rates are the standard deviations			
Table 7.			

$\underline{\boldsymbol{UHP\ N_2}}$	
Run A	133.6 $\pm$ 3.2
Run B	135.2 $\pm$ 4.7
Run C	134.3 $\pm$ 4.5
$\boldsymbol{N_{c_{N_2}} = N_2\ Average}$	134.4 $\pm$ 4.2
Total N_2 count average over 630 seconds	
Table 8.	

§6.2 Calculations

The goal of this research was to experimentally determine the alpha-radiation induced air fluorescence efficiency. Equation three in Chapter 2 provides a way to calculate this quantity using experimentally determined values, manufacturer-provided values, and values derived using the laws of physics. The values found in Table 9 are those that will be used to calculate the alpha-radiation induced fluorescence efficiency observed in an atmosphere of dry air mixture and an atmosphere of $UHP\ N_2$.

Table of Values for Terms in Equation 3			
E_γ		3.68 eV	
r_{sphere}		368 mm	
Q_e		0.25	
N_α		1981350 α/s	
E_α		4.8 MeV	
T_w		0.92	
T_f		0.28	
A_{PMT}		491mm^2	
$N_{c_{air}}$	17.5 +/- 1.8	$N_{c_{N_2}}$	134.4 +/- 4.2
Table 9			

The following is a sample calculation for the alpha radiation induced fluorescence efficiency in air.

$$f_e = \frac{N_{c_{air}} E_\gamma 4\pi r_{sphere}^2}{Q_e N_\alpha E_\alpha T_w T_f A_{PMT}}$$

$$= \frac{\left(17.5 \pm 1.8 \frac{counts}{s}\right)(3.68\ eV)4\pi(368.3mm)^2}{(.25)\left(1981350 \frac{\alpha}{s}\right)(4.8 \times 10^6 eV)(0.92)(0.28)(491\ mm^2)}$$

$$f_{e_{air}} = 4.0 \times 10^{-7},\ \ 3.3 \times 10^{-7}$$

Calculating the alpha radiation induced fluorescence efficiency for N_2 is accomplished using the same method and formula. The only difference in the calculations is the number of counts measured during the experiment.

$$f_{e_{N_2}} = 2.9\ \times 10^{-6},\ \ 2.7 \times 10^{-6}$$

The difference between the fluorescence efficiency values for air and N_2 is due to the reduced percentage of N_2 in air and the quenching of the N_2 fluorescence by the oxygen present in air. [5]

Chapter 7

Conclusions

The final and overarching goal of the experiment was to determine if the process developed could provide the means for an absolute measurement of the air fluorescence efficiency of alpha particles. Before the main experiment was conducted, smaller preliminary experiments were performed in order to calibrate all of the components of the final experiment. These preliminary experiments combined with the final experiment produced a process for measuring the alpha radiation induced fluorescence efficiency in an atmosphere composed of nitrogen or air. It has been demonstrated by the data obtained in the experiment that the process is capable of producing extremely stable and reproducible fluorescence measurements. The measurements are also characterized by the experiment's ability to provide precisely controlled atmospheric conditions. Knowing the precise atmospheric conditions under which the experiment was conducted enhances reproducibility for future experimentation that can yield higher accuracy fluorescence efficiency measurements. These experiments demonstrate a significant advance in reproducibility over previously reported experiments conducted under uncontrolled conditions.

To increase the quantitative accuracy of the fluorescence efficiencies obtained in this experiment, the measurements obtained using the PMT need to be linked to the NIST traceable spectrometer or another NIST traceable device. Better characterization of the alpha source to determine the actual fraction of alphas being emitted instead of the rough estimate of approximately 50% would decrease the amount of uncertainty in the measurements obtained involving the source. If these experiments could have been conducted using a more sensitive NIST traceable spectrometer and a better characterized alpha source, a highly accurate alpha-induced fluorescence efficiency would have been determined. Such experiments are likely in the future. The stability and reproducibility of the data summarized in tables one through eight and the resulting efficiency values demonstrate that the process developed in this experiment to measure the alpha-radiation induced air fluorescence efficiency is the most reliable process developed to date.

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