Experimental Setups for the determination of liquid scintillator properties

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Abstract

This note presents experimental setups for the determination of liquid scintillators properties. The measured light out put of a scintillator is combination of light production and light losses due to interfering processes. We start this note with light production measurements which will be separated into absolute and relative measurements. The following paragraphs we will describe the measurements ideas and setups to obtain information about this interfering processes like attenuation length and light scattering processes.

Contents

1 Introduction

In order to learn more about neutrino physics we have to examine the weak interaction between normal matter and the corresponding neutrinos. Due to the very small cross section for this interaction, all experiments that try detection have to provide a sufficient high number of target protons. To monitor these events with an adequate statistics and on a reasonable time scale, recent neutrino experiments became larger in volume. The current data delivering experiment BOREXINO[2] [3] has a volume of about 300t of liquid scintillator. The planned LENA experiment[4] will contain a volume of 50kt. It will be held in a cylinder which has a diameter of 30m and a height of 100m. Along with the increasing volume of, light losing processes are also increasing and have to be considered carefully for experiments of such dimensions. The target will have to have almost perfect optical properties in order to reach needed sensivity.

The primary aspect of a scintillator is its property to re-emit a constant portion of deposited Energy as scintillation light. The light yield and its extend can be characterized with an absolute light yield measuremnt. If this constant factor(absolute light yield) is known we are able to determine the amount of Energy that was deposited in the scintillator by detecting the emitted light. This measurement provides a number of photons emitted per deposed Energy, which is equal to a constant factor between deposed Energy and emitted light. Nowadays where many scintillators are in use of which all properties are well known we can use a comparing (relative light yield) measurement to obtain the light emission factor.

Unfortunately exists a discrepancy between molecular emitted light and the light that is detected by Photo multiplier tubes (PMT). Theses limiting processes like scintillation light absorption, light scattering and detection efficiency have to be either avoided or at least be well understood and reduced to a minimum. All processes which are not avoidable should be measured and taken into account later on. An exact knowledge of these processes is absolutely necessary to determine the deposited energy out of the detected light. This calculation gets more difficult especially for high volume detectors which increase the possibility of these distracting processes. Some distracting effects of these processes can be improved others only be measured and taken into account.

Experience shows that a proper use of all ingredients in the beginning and a careful handling of the mixture are absolutely crucial to obtain a usable scintillator. Liquid scintillators show certain sensitivity when exposed to UV-light, oxygen and/or elevated temperatures. Is the mixture to one or even more of such conditions subjected over a longer time period, the scintillator base will degrade, the result is a visible yellowish color change of the scintillator.

This note introduces techniques and measurement ideas which can be used to measure the extend of this disturbing effects as well as the determination of the absolute and relative light yield.

1.1 Basic concept of scintillation in organic liquid scintillators

ORGANIC LIQUID SCINTILLATORS are a combination of different ingredients. Basic mixtures are a composition of a liquid solvent (scintillation base) and one wavelength shifter or fluor as it is also called. A solvent consist of molecules which include at least one benzol ring. Theses benzol rings and their individual bindings are the origin of the scintillation process. Each kind of molecule has its own composition and with it a special electron structure. Some structures like benzol rings for example have the ability to scintillate. This emission is a result of a degenerated electron structure which produces an energy gap between two electron band states. In case of benzol rings the structure has an electron band gap that corresponds to an energy of about 4eV. An excited electron in this ring will de-excite over this 4eV band gap and produce scintillation light in the UV-band. PXE, Phenyl-o-Xylylethane a well known scintillator for example produces UV-light of about 280nm. Light of this wavelength has a high probability to get re-absorbed by other molecules of the same kind. In order to avoid re-absorption of scintillation light by the next scintillator base molecule a primary fluor is added. By adding this primary wavelength shifter the de-excitation energy is mainly transferred to the primary Fluor. This energy transfer is dominated beneath 50 Angström by the dexter process. This process describes a non-radiative energy transfer that is based on a dipol-dipol interaction[1]. The primary wavelength shifter however emits the transferred energy radiativly via photons but with a higher wavelength of about 350-400 nm. Re-absorption at this wavelength in the scintillator base is much less probable and therefore is the transparency of the scintillator base for the shifted photons higher. This wavelength shift can be repeated by adding a second wavelength shifter. Using a second fluor the scintillation light can be shifted into the blue part of the visible light, depending on the used fluor (i.e. up to 380-450nm for Bis/MSB). This procedure could be used to increases the detection probability for a photon because some Photomultiplier tubes (PMT) have the highest detection efficiency around 400nm.

In some applications for liquid scintillators it can be necessary to change certain properties of a scintillator like the light yield, number of protons, attenuation length or the density of the scintillator in order to get an applicable scintillator. To change the properties of a scintillator it is possible to dilute the scintillator with a mineral oil(white oil) which has very high optical properties. Some mineral oils have already unpurified an absorption length between 9-12m[7] examples are Do- or Tetradecane. PXE as solvent for instance has unpurified an attenuation length between two and three meters[7]. A mixture of both liquids will produce a scintillator with an attenuation length of with clearly more than 3 meters. In addition will the dilution with mineral oil change the ratio between carbon and hydrogen molecules of the scintillator which changes the number of possible target protons.

The main aspect of a scintillator is its light yield and the knowledge of its extent. Liquid scintillators and their properties are strongly dependent on the amount and fraction of their ingredients. This implies that the best possible combination of ingredients will have to be found for each application and scintillator. In order to find the perfect proportion between a maximum light out put and a minimum of costs for the final scintillator, each ingredient will have to be chosen carefully as well as its proportion in the mixture.

2 Light Production and measurements

The following paragraphs describe the set up and the measurement ideas to determine the physical properties of liquid scintillators.
In this paragraphs we deal with the determination of the light emission (light yield) of liquid scintillators and its measurement. The light yield can be measured either by an absolute or by a relative measurement.
We start each paragraph with the measurement idea and a list of the required equipment in order to provide a short overview. In addition we provide a scheme of the experimental setup for a better understanding a long with a detailed description.

2.1 Relative light yield

2.1.1 Measurement idea

The idea of this measurement is the comparison of two scintillators. To learn more about the light yield of a new mixed probe it is useful to compare this new mixture with a standard scintillator of which all important properties like light yield are already known. This comparison will give a certain percentage of light yield in comparison to the used standards. Well known and therefore used as standard scintillators are liquid scintillators like BC 505, PXE(Phenyl-xylyl-ethen), PC(Pseudocumen) or scintillator crystals like anthracene. Comparing these standard scintillators with any other probe allows us to determine the relative light yield of each new probe.

2.1.2 Required equipment

- a photomultiplier tube (PMT), including readout electronics.
- a γ-source detector (eg. NaI) including readout electronics
- a coincidence logic, gate generators, discriminator, Fan In/ Fan out
- a light-tight box (black or dark box)
- a γ-source eg. ^{137}Cs
- a μ-metal shield for the PMT, to avoid perturbing magnetic fields
- a scintillator probe container (SPC) with cylindrical shape:
    1. made of Teflon(PTFE)
    2. two in/outlet connections to fill/empty/purge the SPC with nitrogen or Scintillator
    3. highly reflective material on the inside
    4. a removable top cover in order to clean the SPC
    5. a removable glass window

2.1.3 Experimental setup

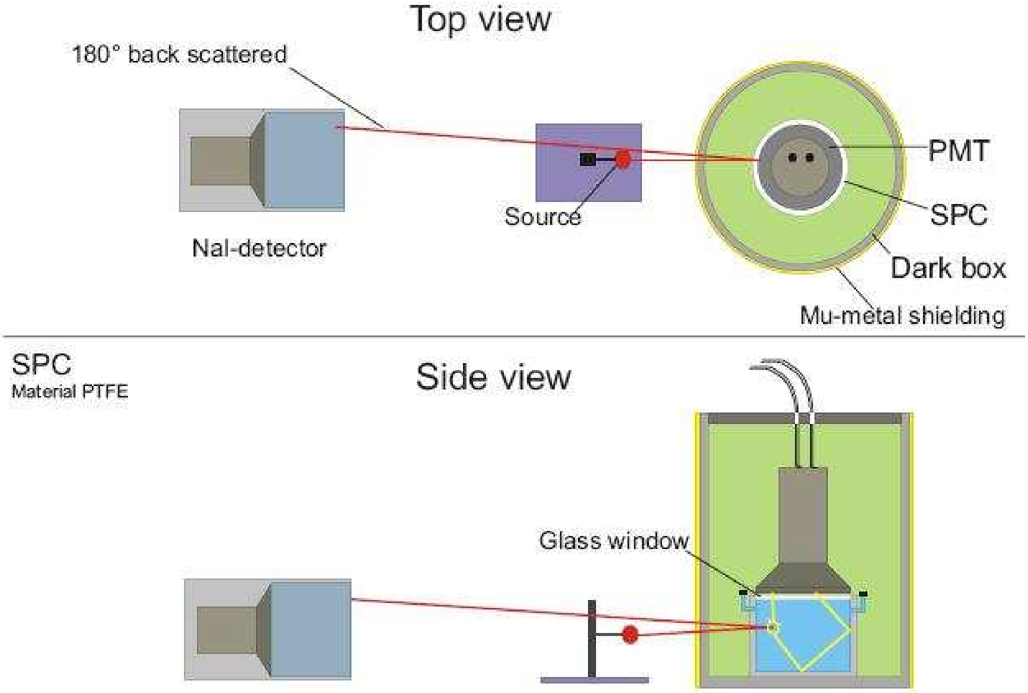

Figure 1: Setup of the relative light yield measurement

For this measurement we excite a fixed volume of scintillator (50-100 ml) with a calibration Source e.g. ^{137}Cs which is a 660 keV γ-source. The experimental setup is displayed in top and side view in Figure 1. The scintillator probe (light blue) is held under nitrogen atmosphere using a SPC(Scintillator Probe Container). A SPC is ideally made of Teflon (PTFE) because it is highly reflecting, is easy to clean and moreover it is inert to chemical reactions, which is necessary for usage with scintillators. The bubble less filled SPC and the PMT are situated in a light tight box (black or dark box), the outer walls of this box[*] are completely covered with a μ-metal shield to avoid interference between the PMT and disturbing magnetic fields. The NaI-detector is used to filter and trigger the measurement. It is placed next to the dark box and at the z-axis height of the SPC. Between SPC and NaI-Detector is a γ-source placed which excites the scintillator with the whole energy spectrum the source is emitting. The needed distance between NaI and this source depends on its activity, in order to avoid a signal pile up. Using the explained layout makes sure that only 180 degree backscattered γ-quants will be detected by the NaI-Detector, which implies a maximum Energy deposition in the scintillator. In order to realize a mono energetic excitation of the scintillator probe the method of Compton back scattering can be used. Compton scattering describes the Energy deposition of a scattered γ-quantum in dependence of its scattering angle which is displayed here.

$$E_{dep} = E_0 \left(1 - \frac{1}{1 + \frac{E_0}{m_e}(1 - cos(\Theta))}) \right)$$

with E_{dep} = deposited energy, E_0 = γ-quant energy, m_e = electron mass, Θ = scattering angel

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[*] Special attention will have to be given to the light tightness of the cable feed troughs

We have maximum energy deposition in the scintillator with a scattering angle of $180°$. This γ-quantum can be identified in an NaI-detector due to its remaining energy[†]. Using this effect we are able to establish a coincidence between the PMT-signal and NaI-signal. This coincidence is triggering the data acquisition system to make sure that only those 480keV events in the scintillator probe are acquired. To lower the amount of wrong triggering events it is usefull to monitor only those events in both detectors which are in the assumed energy window of 480 keV respectively 180 keV for the NaI-Detector. Using such a set up are able to excite both probes with an mono energetic γ-exitation and compare the resulting light yield of both probes.

Signal processing:

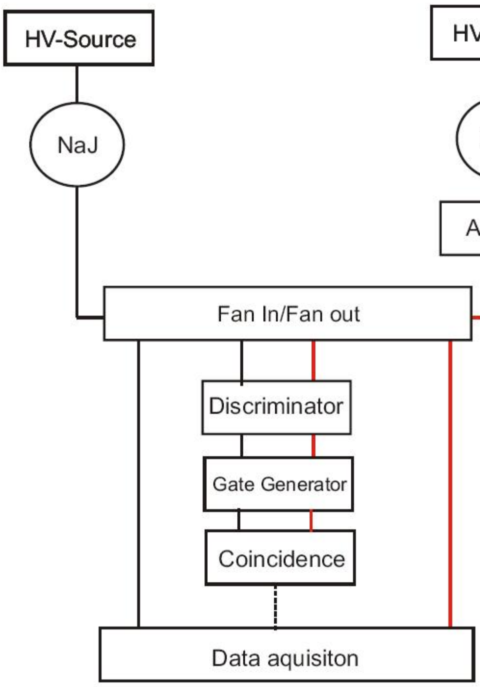

Figure 2: Electronic scheme for the measurement of the relative light yield measurment

The PMT-Signals are amplified and doubled in a Fan in /Fan out, see Figure 2. One signal is lead to the discriminator in order to filter for the assumed energy window. This logical discriminator signal is lead to a gate generator which widens the coincidence time because of the considerable slower NaI-detector. This widened signal is feed into a coincidence logic in order to trigger the Data acquisition system. The second signal is directly fed into the data acquisition system.

The NaI Signal is also doubled in a Fan in /Fan out. One of these signals is fed directly into the data acquisition. The other is (equally to the PMT) sent to a discriminator which filters for the assumed energy window. The resulting logic-discriminator-Signal is also fed into a gate generator. This logic signal is led along with the corresponding signal of the PMT into the coincidenc logic which is triggering the data acquisition.

[†] In case of ^{137}Cs, that emits 660 keV γ's, with 180 degree back scattering, the max. deposited energy in the SPC is around 480 keV and 180 keV in the NaI-Detctor.

2.2 Absolute light yield

This measurement shall provide us the absolute light output of a liquid scintillator. Absolute, means the total number of photons emitted due the mono energetic and well defined excitation of a scintillator probe. This number is a utterly important property of a scintillator as it defines the fraction of energy that is emitted in scintillation light. This fraction allows us to use a scintillator as a detector material. The absolute light yield is done mostly for the reasons of comparability normalized to a energy deposition of one MeV.

2.2.1 Measurement idea

For this measurement, we compare multi photon scintillation pulses resulting from known energy excitation with single photon pulses in order to get the number of detected photons. To achieve this we analyze the pulse shape areas[‡] of multi and single photon pulses. The ratio of both pulses provides us with the number of detected photons. To draw a conclusion towards our aim, namely the number of emitted and not detected photons per MeV, we have to determine the light collection efficiency of our setup. For the light collection efficiency we have to make the assumption that the light is homogeneously emitted in the whole solid angle. Moreover we have to assume that the collected light the result of scintillation and not the result of reflection. If those assumptions can't be made, separate measurements aiming for these properties will have to be done. We know the amount of photoelectrons that were detected in a solid angle cut out by the diameter and distance of the PMT. If we use the assumptions (homogeneity and non-reflection) we are able to scale the results up to a solid angle of 4π. By using the given PMT quantum efficiency we are able to estimate the total amount of photons primarily emitted by the probe. By using a small instead of high volume SPC, we don't have to care for absorption or light scattering effects.

In this set up Compton back scattering was used to excite the scintillator probe with a defined energy. A defined excitation can also be done by using cosmic Muons and the known energy deposition per cm target-material. Another possibility is the use of a sodium source (^{22}Na). This source is a e^+-emitter. These positrons annihilate within the source and emit two 511keV γ-rays which have $180°$ degree to each other. Unfortunately this method is most useful when the SPC is big enough to be sure that the whole 511keV γ-ray is fully absorbed by the target. Therefore are not all of these excitation methods useable, for small SPC's.

[‡] The area of a sample pulse is proportional to the charge of the PMT-Signal

2.2.2 Required equipment

- a photomultiplier tube (PMT) including readout electronics.
- a γ-source detector (eg. NaI) including readout electronics
- a coincidence logic, gate generator, discriminator, Fan In/ Fan out
- a light-tight box (black or dark box)
- a γ-source i.e. ^{137}Cs
- a μ-metal shield for the PMT to avoid perturbing magnetic fields
- a scintillator probe container (SPC) with cylindrical shape
    1. made of transparent material, i.e. quartz glass
    2. two in/outlet connections to fill/empty/purge the SPC with nitrogen or Scintillator
    3. a removable top cover in order to allow cleaning the SPC
    4. a reflection suppressor i.e. black felt

2.2.3 Experimental Setup

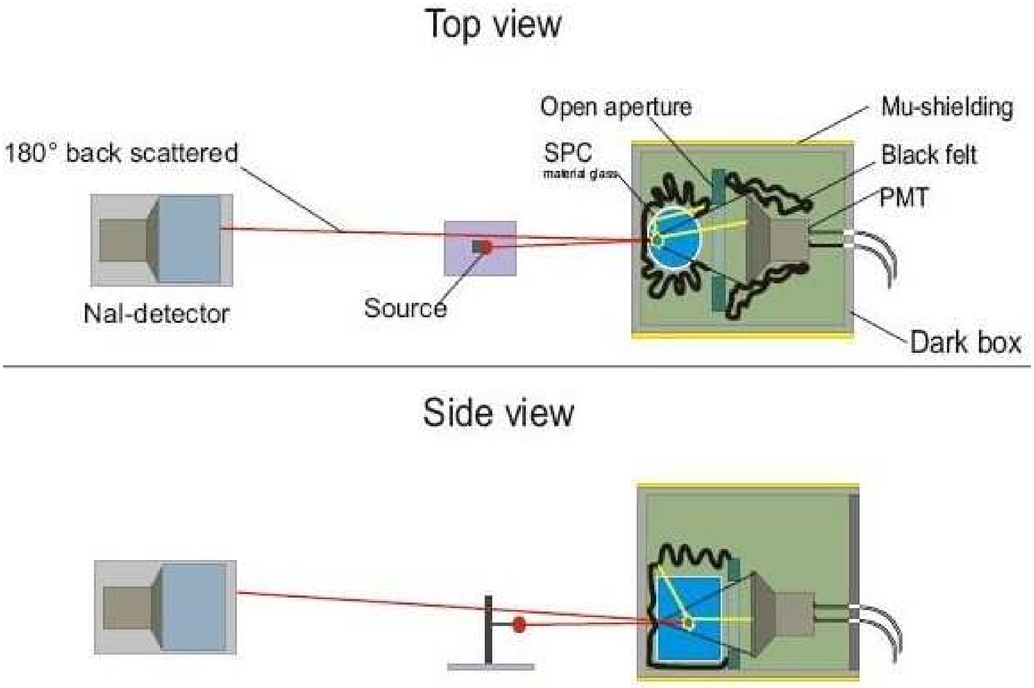

Figure 3: Experimental setup for the absolute light yield measuremnts

This setup and its basic lay out is very similar to the setup of the former paragraph. It also uses Compton back scattering as excitation method. The main changes are made to the SPC. Since we assume non-reflectivity we rather use a light absorbing or transparent material. Using a transparent SPC implies to stop the light that has not been emitted but reflected in the direction of the PMT, in order to reduce reflections with in the black box. This is realized by surrounding the SPC with a light absorbing material like black felt, which is laid loosely around the SPC. With this technique we have just to care for reflection on the inner glass walls of the SPC. This inner reflection will have to be measured and taken into account. Figure 3 shows the new layout including the black felt used as light trap.

MEASUREMENT OF THE SINGLE PHOTO PEAK

One possibility of measurement is to analyze the thermal noise of the PMT while the voltage is near the PMT's maximum. We place the PMT in a dark box and apply between 80-90 percent of its maximum voltage. The temperature and the high voltage applied on the dynodes will release electrons out of the dynodes.

Each dynode could set free an electron, but the signal with the highest charge will be due to an electron that is emitted on the first dynode. All other dynodes would produce a lower charge (signal area) due to the lower number of electron multiplication (electron avalanche multiplication per dynode). Acquiring these pulses and analyzing their area, we find an area-spectra. This spectrum shows us an exponentially dropping noise line and added to this a not Gaussian distributed signal. The maximum of this spectra signal marks the area of the single photo peak.

A different approach is the use of a LED-Diode excited with a periodical square signal. The triggered events are acquired and recognized. To reduce the number of photons in a triggered pulse the signal amplitude and duration time of the pulse which is sent to the LED is lower steadily. The square signal will reach a level where not every triggered event produces a detected photon. This will lower the possibility for a multiple photon triggered event, which will lead to single photon events which form the wanted signal.

MEASUREMENT OF AN ENERGY DEFINED SCINTILLATOR SIGNAL

For this excitation we use the same Compton back scattering method that were already applied in the former paragraph, see 2.1.3 and Figure 2).

QUANTUM COLLECTING EFFICIENCY

In order to close the gap between the detected number of photoelectrons of the PMT and the emitted photons from the scintillator, we have to know the quantum collecting efficiency of the setup. Therefore we need to know

- Observed solid angle of the PMT
- Quantum efficiency of the used PMT
- Assumptions have to be correct

Two assumptions are necessary: First, all detected light is the result of a scintillator emission and not a reflection and second the scintillation light is homogeneously emitted over the full 4π solid angle.

The observed solid angle is strongly dependent on the exact distance between light production[§] and PMT-cathode as well as the areas of possible energy deposition and the PMT cathode itself. A slight error in these parameters will lead to a considerable change of the estimated light yield.

First we assumed that scintillation photons can leave the SPC in all directions without being internally reflected in the SPC. All detected photons would therefore originally result from a scintillation process which is illuminating the PMT-observed solid angle. To justify such an assumption we use a SPC that is transparent and cylindrical. The SPC is covered (except the solid angle of the PMT) with a light absorbing material that is laid loosely around it in order to provide light traps rather than a black surface. The usage of black felt as absorber material showed good results.

The second assumption allows us to assume that the number of photons observed in a certain solid angle would not change regardless from where this angle is observed. With this we are able to scale the observed solid angle up to a 4π, and with it the total amount of detected photons. Internal reflections would falsely raise the light yield estimation dramatically due to this up scaling.

In a real experimental, due to the set up, the shape and material of the SPC inner reflections are not avoidable. These still remaining reflections will have to be observed and taken into account. This can be done by simulating light pulses with a LED. If the SPC is full of distilled water we avoid unnecessary reflections on the inner sides of the SPC. These simulated reflections can be taken into account as background.

Furthermore, each PMT has its own quantum efficiency. This number is a property which describes the efficiency for photon detection. This value is tested and written down in the specification letter of each new PMT. For an 8 Inch PMT from ETL 9354KB as an example, the efficiency is 25,7 percent[9].

[§] The volume of light production is not easy to identify because of the probability variations for the penetration depths of a γ-ray before it is able depose its energy.

3 Light attenuation and measurments

In the following paragraphs we introduce the setups and measurement ideas which are needed to measure the fraction of light scattering and absorption processes which lead to a combined light attenuation. The combined attenuation length of a scintillator can be measured as well as its scattering length. With this knowledge it is possible to calculate the absorption length of a scintillator which is normally hard to measure. The following paragraphs introduce in detail measurements ideas, setups and schemes of experimental setups which are needed to measure the attenuation length and scattering length of a scintillator. We start each paragraph with the measurement idea and a list of the required equipment in order to provide a short overview.

3.1 Attenuation length

This measurement aims for the intensity loss of scintillation light while it is propagating through the scintillator itself. The attenuation length is the distance after which the scintillation light has lost a factor of e^{-1} of its initial intensity. This loss is the result of light scattering and re-absorption as mentioned earlier. It is especially important for high volume experiments and can't be neglected since the attenuation length of some solvents is in the dimension of 2-9 meters without purification. In order to measure this non-avoidable intensity loss, we measure this integrated loss which is given by:

$$dI = -\left(\frac{I}{\lambda_{att}}\right) dx$$

and integrated

$$I(x) = I_o e^{-\frac{x}{\lambda_{abs}}} e^{-\frac{x}{\lambda_{scat}}} = e^{-\frac{x}{\lambda_{att}}}$$

with I_0=initial Intensity, λ_{abs} = absorption length, λ_{scat} = scattering length, λ_{att} = attenuation length

In a second measurement which will be described in the next paragraph, we deal with the measurement of these two light absorbing processes, the light scattering. This will give us the possibility to obtain indirectly the influence of the second process which is absorption. It is possible to measure the attenuation more easily by using a spectrometer, which has furthermore the advantage to measure a whole band of spectral light. Anyway is the first described measurement the preferred one, because the spectrometer normally uses a SPC with a diameter of max. 10 cm. With such a small SPC it is not feasible to obtain doubtless results for attenuation length above 10m, which is however the dimensions needed for future projects.

3.1.1 Measurement idea

To measure the integrated intensity loss we compare three intensity measurements. All use the setup shown in Fig 4. One measurement is done without the SPC in order to obtain the full intensity of the LED-signal pulse. The second measurement uses an either empty or distilled water filled SPC, in order to obtain knowledge about intensity lowering reflection on the SPC's glass windows.
Knowing all intensity lowering influences of the SPC, that we have to take into account, we can start to measure the attenuation length of a scintillator probe. We use a scintillator filled SPC to obtain the attenuation properties of this scintillator. These measurements are repeated with three different sizes of SPC's 1m, 50cm, 25cm in length, to collect enough data points to fit the exponential function of the attenuation length. These data point are acquired with one LED emitting one wavelength. Scintillators, however have different absorption properties depending on the used wavelength. To obtain knowledge about its wavelength depending absorption we use different LED's(405nm, 420nm, 450nm). This measurement is due to the high number of combinations that can be made very time consuming. Furthermore each change of setup is subdued to the problem of reaching comparable experimental conditions. Comparing the over all intensity with the empty (or distilled water filled) SPC allows to estimate the reflections due to the SPC which we have to take into account. Comparing the scintillator signals with the overall intensity measurement provides us the total intensity loss due to absorption and scattering. All these measurements assume that the scattered light within the SPC is not reflected into the PMT. We justify this assumption by reducing the internal SPC reflections to minimum.

3.1.2 Required equipment

- a photomultiplier tube (PMT) including readout electronics
- a LED with wavelength around 420nm
- a coincidence logic, gate generator, pulse generator, Fan In/ Fan out
- a light-tight box (black or dark box)
- a converging lens
- a small aperture
- two polarization filters
- a reflection light absorber i.e black felt
- three scintillator probe containers (SPC) with cylindrical shape
    1. made of stainless steel
    2. blackened (low reflectivity) and passivated on the inside
    3. three different sizes length (1m, 50cm, 25cm), diameter 5cm
    4. two in/outlet connections to fill/empty/purge the SPC with nitrogen or Scintillator
    5. two removable top covers in order to clean the SPC
    6. two removable glass windows

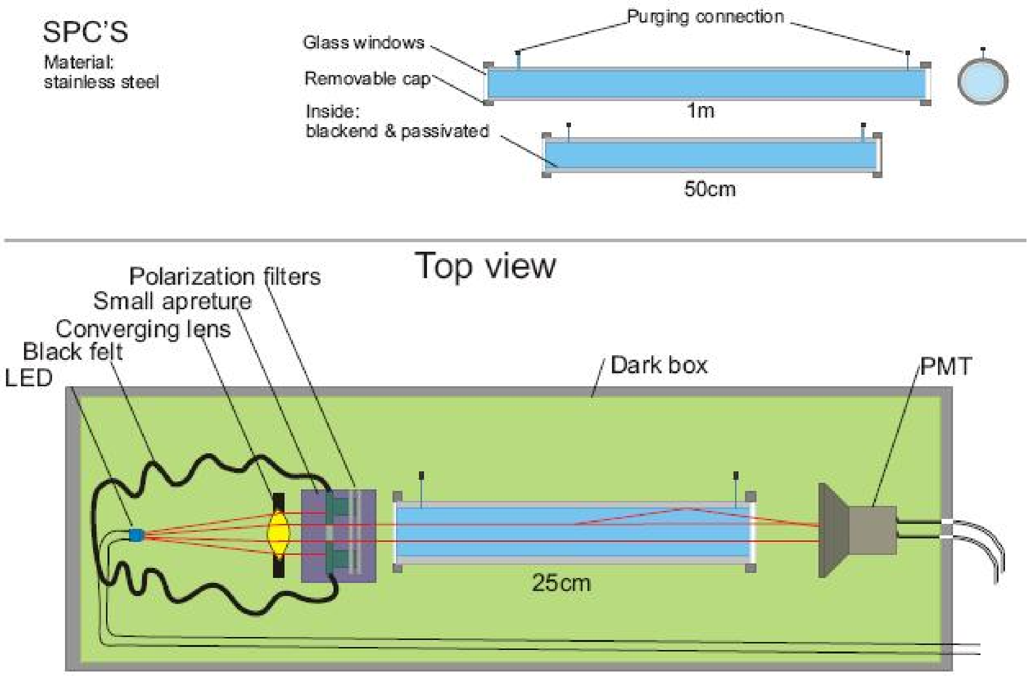

Figure 4: Experimental setup for the attenuation length measurement

3.1.3 Experimental setup

The LED is placed in the focal point of a converging lens which parallelizes the emitted photons. This parallel beam is sent through an aperture of about 1-2cm diameter. With this technique we obtain a narrow and parallel light beam with which we avoid unnecessary reflections on the SPC inner walls. All these parts are well enveloped by black felt to avoid reflections (or direct light from the LED) within the black box that could be seen by the PMT. Placed right in front of this aperture are two polarization filters to reduce the light pulse intensity as mentioned above. This parallel, narrow and intensity regulated pulses are sent trough the scintillator to be detected at the PMT-cathode.
The SPC itself is a blackened and passivated metal tube. Blackened in order to avoid reflections of scattered light which could be seen by the PMT and chemical passivated to avoid reactions between the scintillator and the SPC. The passivation of the SPC has two positive effects. First, the SPC will not be oxidized or chemically dissolved in any way and second the scintillator probe will not suffer from harmful chemical reactions, while it is in contact with the SPC. For this measurement three different SPC's have to be used with a diameter of 5cm and a length of 1m, 50cm and 25cm. Each one has a glass window at the front and at the end, which are fixed by a removable end cap. In addition each tube has two small connections for purging the scintillator after filling.

MEASURING THE TOTAL LIGHT INTENSITY

For all measurements we produce LED-Pulses with a square wave signal of 30ns and 4 Volts height provided by a pulse generator which is fed by a gate generator. These fixed input parameters are used for all LED's. LED's of different wavelength have by a factor of 10 different light output intensities. Two polarization filters in front of the aperture are used to regulate the varying intensities in order to remain in the linear detection mode of the PMT. Figure**??** shows the details of this setup.

We assume the PMT signal area of a single photon event is already known for this setup. Using the described LED pulses in a setup without SPC will give us the total light intensity of a pulse, and with the known single photon charge we have the number of photons per LED-pulse.

Signal processing:

A gate generator triggers the pulse generator of the LED. This trigger signal starts also the Data acquisition system and a PMT pulse is acquired. Figure5 shows a diagram of this setup.

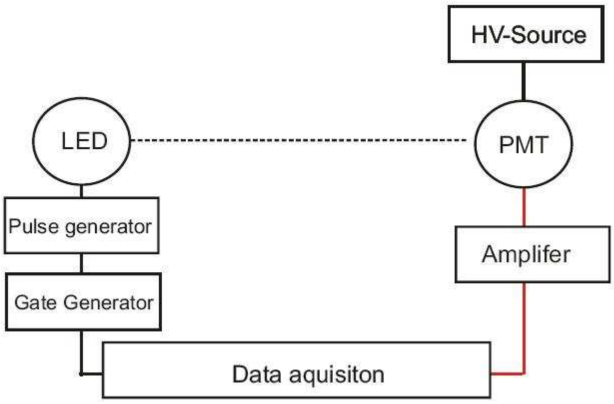

Figure 5: Electronic setup for the attenuation length measurement

MEASURING THE LIGHT INTENSITY LOSS DUE TO REFLECTIONS

By inserting the SPC and acquiring pulses trough an empty SPC will show the amount of intensity loss that is only due to the SPC, meaning the reflections on the 2 glass windows or unwanted reflections on the SPC walls. In order to know the extent of these non-avoidable reflections we measure their intensity. The light beam has to pass two glass windows; on each of them a reflection will reduce the transmitted intensity. A reflection coefficient can be calculated by using the geometry of this setup (reflection of $180°$). This calculation is dependent on the refractive index of the medium and independent on the light polarization, with:

$$R = \left(\frac{n_{Air} - n_{Glass}}{n_{Air} + n_{Glass}} \right)^2$$

R= Reflection coefficient, (n_{Air},n_{Glass})= Refractive indices

This leads to a reflection coefficient of 0.04 per medium change. The total loss of intensity using an empty SPC, meaning 4 medium changes, will therefore be around 15 percent.

In order to have a comparable experimental setup we have to keep in mind that the scintillator filled SPC has 2(glass-to-air) and 2(glass-to-probe) medium changes of which the last will make almost no reflection due to its similar refractive index. To face this we could fill the SPC with distilled water, which has a very high attenuation length of about 60m[6]. With this trick we are able to imitate the reality of the measurement more accurately. Because of the varying quality of distilled water and the re-ionization when in contact with the SPC, this operation may a questionable one.

MEASURING THE LIGHT INTENSITY LOSS IN SCINTILLATOR PROBE

For this measurement we insert a SPC filled with scintillator and acquire sample pulses exactly like the previous measurements. The measured intensity has to be corrected by the reflection losses due to the SPC and compared to the intensity that was initially emitted by the LED. This measurement is repeated for each SPC length in order to obtain more data points on which the exponential function of the attenuation length can be fitted. Light scattering has to be avoided as efficient as possible. However, after a filling and purging process of a SPC the liquid is filled with gas bubbles that are scattering targets, therefore has every SPC to stay immobile for several hours before a measurement is acquired. These absolutely unwanted reflections would have increasing effects, with a increasing length of the SPC.

CALCULATING THE ATTENUATION LENGTH

The attenuation of light scattering is given by:

$$I(x) = I_0 e^{-\frac{x}{\lambda_{att}}}$$

To obtain the attenuation length we have to compare the Intensity I_0 with $I(x)$. In addition we have to tae into account the occurring reflections on the glass surfaces. In a filled SPC are two surfaces which produce considerable reflections, the 2(glass-to-air) surfaces[¶]. Each medium changes produces a four percent reflection. This makes a Transmission coefficient of T=0.96. The I_0 has to be corrected with this coefficient for each counting medium change. Using α= $I(x)/I_0$ and T as Transmission coefficient we get for a scintillator filled setup the attenuation length of:

$$\lambda_{att} = \ln \frac{-x}{\frac{\alpha}{T^2}}$$

[¶] The surfaces between scintillator and glass don't produce much reflections due to the similar refractive index of both materials

3.2 Light scattering

Light scattering has two main reasons Rayleigh-scattering and Mie-scattering. The Rayleigh-process describes scattering of photons on bound electrons whereas the Mie-process a photon scattering on particles describes, which are bigger than the wavelength of the scattered light. Considering the nature of both processes makes clear that Rayleigh scattering is an intrinsic property and not avoidable whereas Mie-scattering can be avoided (minimized) by reducing the number of suspended particles in the scintillator mixture. Rayleigh scattering has a certain characteristic with which both scattering processes can be distinguished. The scattering process is equal in 4Π therefore is an observation of a small but defined solid angle enough to up scale the number of scattered photons to the full solid angle possible. Only the polarization of the scattered photons is dependent on the scattering angle. So is a circular polarized photon (after scattering) with a scattering angle of 90° linear polarized. This effect is also a good possibility to distinguish Rayleigh and Mie-scattering and with it the non-avoidable (intrinsic) scattering effects from avoidable scattering effects. For the next paragraphs we assume that Rayleigh-Scattering is the dominant effect whereas Mie-Scattering can be neglected.

3.2.1 Measurement idea

To measure the scattering length we count the number of scattered photons in a scintillator probe which are scattered in a fixed and known solid angle. To use this information we also have to know the number of Photons which were in the original light pulse itself. If we can assume a negligible absorption in small SPC's it is enough to count the number of transmitted photons. For the calculation of the scattering length it is necessary to assume Rayleigh scattering as dominant scattering process which is reasonable after a scintillator purification. In addition we have to assume that the inserted LED light pulses are not absorbed but scattered which is also reasonable is a small Probe. LED-pulses are sent through a scintillator probe. A PMT measures the transmitted light(0°) and the scattered light(90°). This can be done either by two PMT's at the same time or by one PMT which has to changes its observing angular between 0° and 90°. This setup is shown in Figure6. By knowing the number of photons that are emitted by a LED-Pulse and knowing the number of scattered photons in a certain solid angle we are able to calculate the scattering length of the scintillator probe.

The exact reconstruction of the scattering process is not trivial and should therefore be done with a simulation which allows us to cross check our experimental results.

3.2.2 Required equipment

- a photomultiplier tube (PMT) incl. readout electronics
- a LED with a wavelength of 420nm
- a coincidence logic, gate generator, pulse generator, Fan In/ Fan out
- a light-tight box (black or dark box)
- a converging lens
- a small aperture
- two polarization filters
- a reflection light absorber i.e black felt
- a scintillator probe container (SPC) with cylindrical shape
    1. made of transparent material i.e. quartz glass
    2. two in/outlet connections to fill/empty/purge the SPC with nitrogen or Scintillator
    3. a removable top cover in order to clean the SPC
    4. a reflection suppressor i.e. black felt

3.2.3 Experimental setup

To measure transmitted and scattered photons we use the set up shown in Figure6. The PMT position 1 is used to measure transmitted photons whereas position 2 is used to detect the scattered photons. In position 1 the aperture in front of the PMT is fully open. In position 2 is the opening of the aperture very small in order to observe only a short light path from which the scattered photons can be originating from. The volume from which the scattered photons are originating should be kept as small as possible in order to know the spot of scattering. Due to that the LED is placed in the focal point of an converging lens. This parallel beam is sent trough an aperture of about 1-2cm diameter. Due to that we obtain a narrow and parallel light beam with which we again avoid unnecessary big scattering volume. This light beam can be adjusted in intensity with the help of two polarization filters which are placed right in front of this aperture.
All these light producing parts are well enveloped by black felt to avoid reflections or direct light from the LED that could be seen by the PMT. The whole set up is situated in a black or dark box.

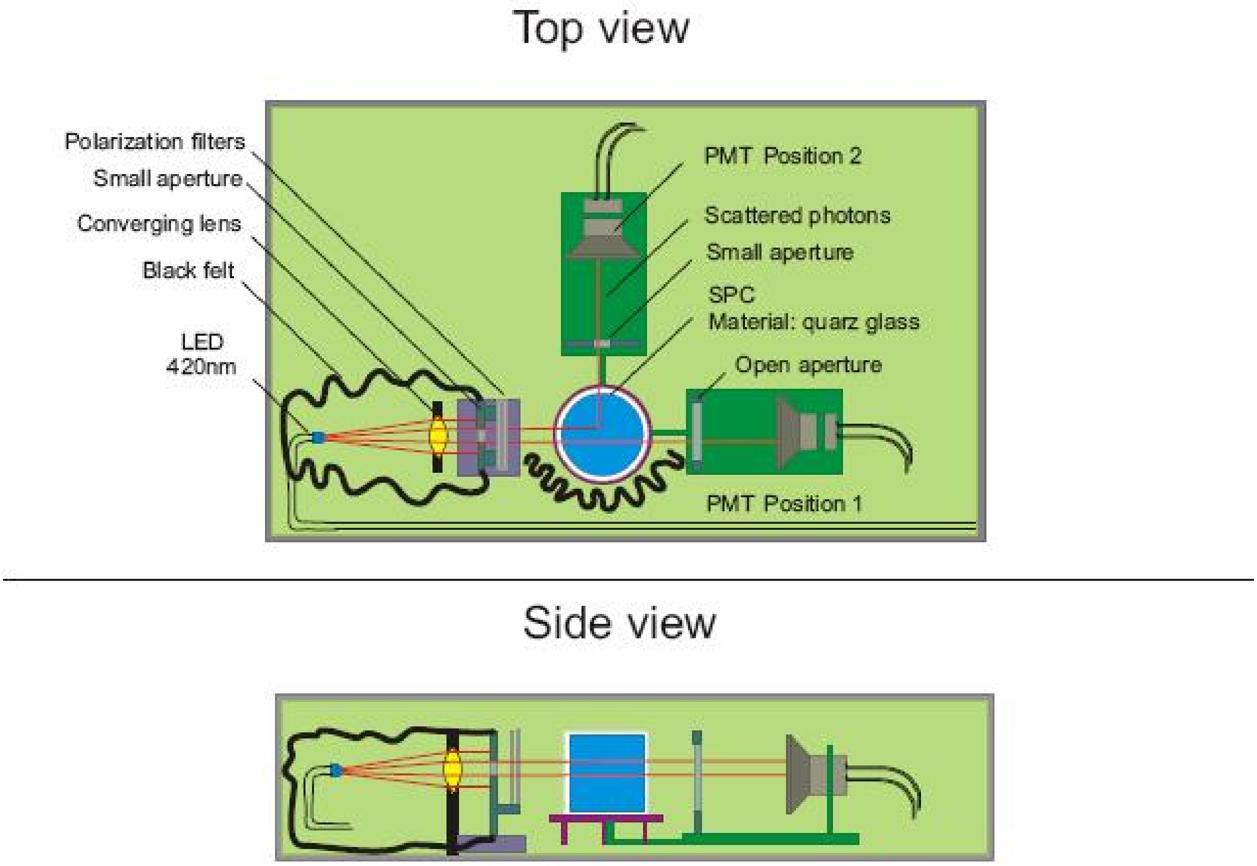

Figure 6: Experimental setup to measure the light scattering

Calculating the absorption length

Together with the measurements of the former paragraph (attenuation length) and this paragraph(scattering length) it is it possible to obtain information about the absorption length. The relation between attenuation, absorption and scattering length is:

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scat}}$$

λ_{att}= attenuation length, λ_{abs}= absorption length, λ_{scat}= scattering length

Using this relation we are able to calculate the absorption length by using the obtained experimental data of scattering length and attenuation length.

3.2.4 Light scattering theory

Theoretical calculation of the scattering length

The scattering length can also be calculated; therefore we have to find a connection between the total cross section and the scattering length: This connection can be found using (assuming no absorption in the small SPC) light transmission function which is given by:

$$N(x) = N_0 e^{-n\sigma_{tot}x} = N_0 e^{-\frac{x}{\lambda_{scat}}}$$

N_0=number of photons ,$N(x)$=number of not scatterd photons, $n = N/V$= density of Targets, σ_{tot}= total crossection

$$\lambda_{scat} = \frac{1}{n\sigma_{tot}}$$

With this relation we are able to calculate the scattering length in dependence of the total crossection for the scattering process and the number of targets per volume.

Calculating the total cross section of Rayleigh-scattering

The scattering has two main reasons Rayleigh-scattering and Mie-scattering. The Rayleigh-process describes the scattering of photons on bound electrons. The excited electron oscillates in the same direction and phase like the E-vector of the exciting photons. This electron-oscillation is suppressed by the forces of the bound electron, which slows down the oscillation. For this dampend dynamics will the total cross section for this scattering be the Thomsons-cross section multiplied by the typical ω^4 dependence, which includes the excitation wavelength as well:

$$\sigma_{tot,\omega 0} = \sigma_T \left(\frac{\omega}{\omega_0}\right)^4 = \frac{8\pi}{3}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2 \left(\frac{\lambda}{\lambda_0}\right)^4 = \frac{8\pi}{3} r_e^2 \left(\frac{\lambda}{\lambda_0}\right)^4$$

with σ_T= Thomson cross section and r_e^2= 2.9fm the classical radius of an electron

Due to this oscillation (and the emission behavior of a dipole) the scattered light is polarized depending on the scattering angle. The polarization is maximized for a scattering angle of 90°. This behavior is described by the differential cross section in dependence of the scattering angle of the light (φ). This differential crossection is given by:

$$\frac{d\sigma}{d\Omega} = r_e^2 \left(\frac{\lambda_0}{\lambda}\right)^4 \frac{1 + cos^2(\varphi)}{2}$$

Integrating this differential cross section over the whole solid angle gives us the total crossection already given above.

Using the absorption wavelength of a solvent i.e.PXE (26 5nm) and the excitation wavelength of 430nm we get for the total cross section of a Rayleigh scattering process:

$$\sigma_{tot,\omega 0} = \sigma_T = \frac{8\pi}{3} (2.9fm)^2 \left(\frac{265nm}{430nm}\right)^4 = 10.2 \times 10^{-30} m^2 \equiv 10.2fm^2$$

PXE has two benzyl rings of which both have a first excitation level, therefore could be said that the crossection is as well doubled to

$$\sigma_{tot} \approx 20(fm)^2$$

Calculating the target density n

The target density i.e. for PXE can be calculated by:

$$n_{PXE} = \frac{\rho_{PXE} N_A}{m_{PXE}} = 2.8 \times 10^{27} m^{-3}$$

with ρ_{PXE}= 0.985kg/l, N_A=6.022 $\times 10^{23} \frac{1}{mol}$, m_{PXE}=210.2u

Scattering length

Using the relation of Target density and total cross section, given above, we can derive a scattering length of:

λ_{scat}=35m(with 10.2fm^2) and 17,5m (with 20.4fm^2)

Mie-scattering

The Mie-process describes photon scattering on particles bigger than the wavelength of the light. Considering the nature of both processes makes clear that Mie-scattering can be avoided by reducing the number of suspended particles in the scintillator. The scattering characteristic of a Mie-process are different to the Rayleigh-process. The angular distribution of Mie-scattered light is asymmetric, it is mainly emitted in forward direction. Further more is the scattered light strongly dependent on the particle size. The differential cross section the therefore described by a Henyey-Greenstein function[7]

$$\frac{d\sigma}{d\Omega} \alpha \frac{1 - g^2}{\sqrt{(1 + g^2 - 2gcos(\varphi))^3}}$$

Fortunately has the Rayleigh process the advantage to produce polarized scattering light (maximal at 90° scattering) whereas Mie-scattering has just an influence on the polarization when the targets are deformed normally has Mie-scattering no influence on the polarization. This difference can be used to identify the dominant scattering process.

4 References

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