Scintillator Material Characterisation for SABRE Dark Matter Detector

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1 Introduction

There is a large and convincing body of astrophysical evidence that most of the matter in the universe is dark. Understanding the nature of dark matter is one of the most important problems in modern physics. One class of candidates for dark matter is Weakly Interacting Massive Particles, which the DAMA/Libra experiment claims to have detected. However, due to controversy surrounding the DAMA/Libra results, there is need for another experiment to verify them. SABRE is one such experiment, which will search for an annually modulating signal due to the Earth's motion around the sun. It utilises a liquid scintillator veto for improved background rejection. Linear-alkyl benzene, with bis-MSB and PPO additives, is being used as the liquid scintillator. (The mixture will be referred as LAB in this report.) Its light yield can be easily degraded by the presence of contaminates, so compatibility testing is needed to ensure that it is not degraded by the materials used in the construction of the detector. Its important to know the decay time of scintillator for proper working of simulation models. This project revolves around the measurement of light yield and decay time of LAB.

2 Experimental Preparation

The procured LAB was impure and so it had to be distilled to remove any contaminates. We used a vacuum distillation setup as shown in figure 1. The vacuum pump was used to lower the boiling point of the LAB to approximately 120°C at 6 mB. The distilled LAB was used for testing. The

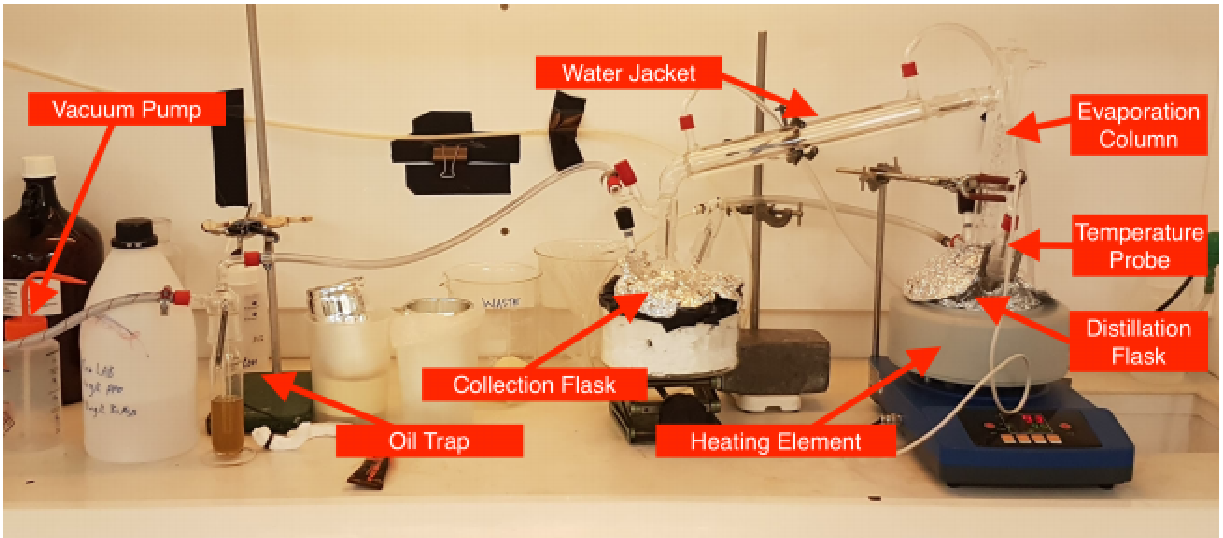

Figure 1: Distillation Setup

containers, used to store distilled LAB, were cleaned using a mixture of ethanol and water and dried using pressurized N_2. The same procedure was repeated for pieces of sample. (Sample means different material which will be present in the detector). Different samples were kept immersed in the LAB in different containers. Two vials contained LAB only and no sample. These are used as a reference for light yield measurement and used for time decay measurement. The light yield measurements were made weekly. Every week 10 grams of sample is pipeted out from the container and put in vial. They are put back again in the containers after the light yield measurements.

3 Light Yield Measurement

To investigate light yield we measure the spectrum of a caesium-137 source using a sample of the liquid scintillator that we wish to test. A 5 micro-Curie caesium-137 source is placed in a dark box along with a Photo-Multiplier Tube (PMT) and the scintillator sample. The use of a dark box is necessary to prevent natural light from drowning-out emissions from the scintillator. The PMT was fed through an amplifier and into an MCA (the FastComtec MCA-3 Series / P7882) to record the emission spectrum.

Since the same spectrum is being measured in each case, and, given that

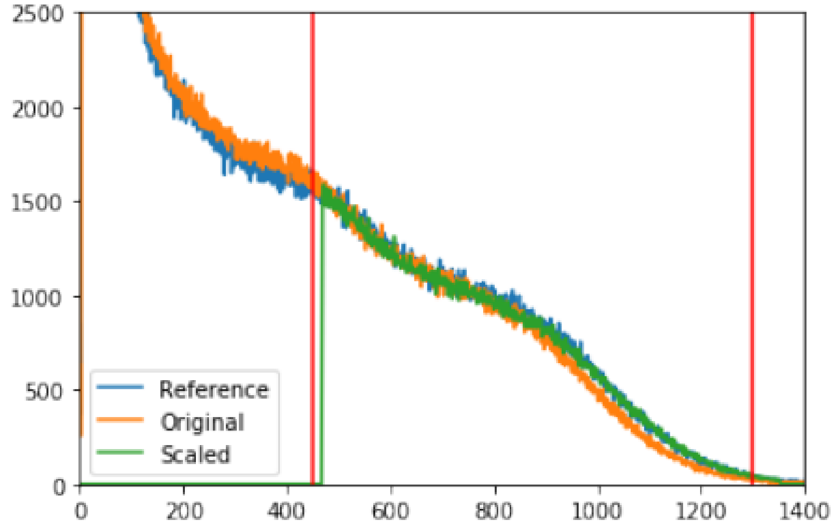

Figure 2: Spectrogram Scaling

the same exposure time and quantity of scintillator is used, there should be approximately the same number of registered events. Therefore, the only difference between spectra should be the redistribution of counts across bins due to changes in relative light yield. So, by redistributing the counts in one spectrogram and comparing it to a reference spectrogram, a best fit can be found corresponding to some scaling factor (figure 2). For a range of trial scaling factors, the distribution of chi-squared values between the scaled and reference spectrogram can be calculated. The relative light yield value can then be taken as the scaling factor corresponding to the minimum chi-squared value. Since the counts in the spectrogram are normally distributed, the required chi-squared value for a particular confidence level in the scaling factor can be calculated from the inverse cumulative distribution function of the chi-squared distribution. This gives a level above the minimum chi-squared value across which the width of the distribution gives the required confidence interval. This confidence interval is directly related to the statistical uncertainty, and if calculated for a confidence of 68.2% will give one standard deviation.

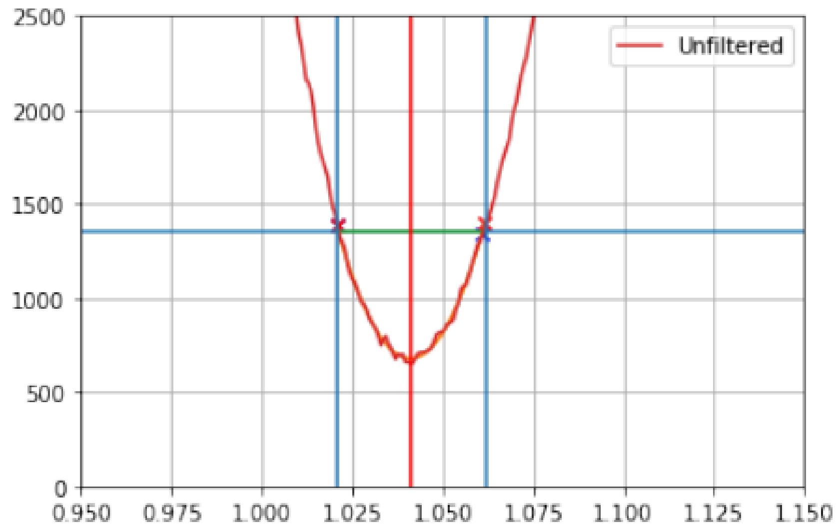

Figure 3: Chi-Squared Distribution

3.1 Testing of the methodology

To test the experimental and data-analysis method, 20 minutes measurement on same sample was done for 7 times. The relative light yield value was calculated by comparing it to the mean of all the measurements. The light yield value was seen to be decreasing with time (figure 4). Investigating the PMT revealed presence of dirt on it. It was concluded that accumulation of dirt on PMT with time is the reason of the decrease in measured time. So, it was decided to wipe the PMT before start of a set of measurement and wipe the base of each vial before putting it on PMT. This measure resolved the problem.

To test the calculation of statistical uncertainty, 60 minutes measurement on same sample was done for 16 times. We find the statistical uncertainty for each measurement from the chisquare method as described previously and calculate the mean statistical uncertainty. We also find the total uncertainty by finding the variance in lightyield values obtained from these 16 measurements. When these 2 values are compared, it was found that there was overestimation of statistical uncertainty by a factor of 30 when calculated with chisquare method.

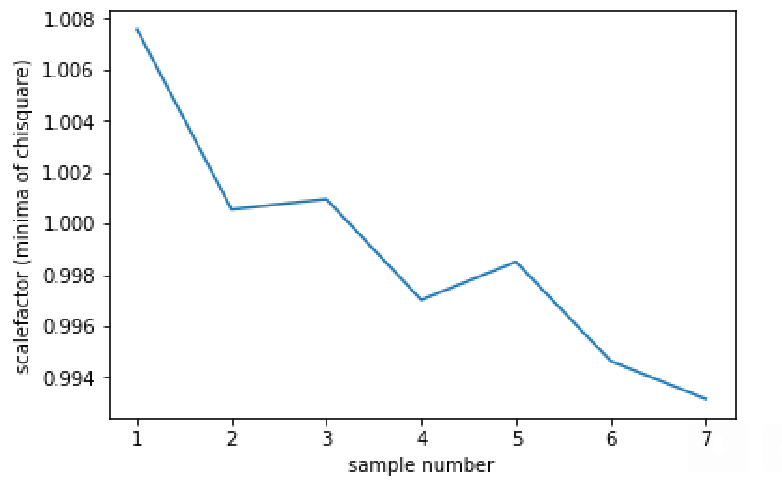

Figure 4: Light Yield Values

If degree of freedom was assumed to be equal to one (i.e. equal to number of parameters to be fitted) for calculation by chisquare method, the results were as expected; the statistical uncertainty came out to be less than total uncertainty and it was less for 60 minutes measurement compared to 20 minutes measurement. But according to literature, degree of freedom is assumed to be equal to number of bins used for comparison. So, though the previous assumption mysteriously produces the expected result, it is violating the rules of statistics.

After being unable to solve the mentioned problem from written function, standard library for calculation of statistical uncertainty was considered. But the standard easy-to-use curve-fitting modules require same size of array containing the independent and dependent values while in the case of the scaling, the size of array containing dependent values depends on the scaling factor; and so these standard modules cannot be modified for our purpose.

Though the code was giving incorrect value of statistical uncertainty, it was desired to test whether the code calculates correct relative lightyield value (the parameter of interest). To test it, a spectrum of normally distributed values was generated. It was multiplied with different scaling values to get different test spectra. The chisquare method calculated the correct lightyield value (the scaling value) for each of the spectra. (The used scaling values were between 0.97 and 1/0.97 as the relative light yield values for the test samples are expected to be in this region.)

4 Decay Time Measurement

To investigate decay time, we measure the spectrum of a ^{22}Na source using two scintillators. The setup consists of liquid scintillator with PMT and BaF_2 with PMT; both inside the dark box. ^{22}Na source is put in between the two scintillators, so that both the scintillators record the same positron emission event. Both the PMT is fed through the amplifiers which is then fed through Constant Fraction Discriminator (CFD) whose output is then fed through coincidence logic. The output of coincidence logic and PMTs is fed into digitizer which records the PMTs signals only if coindince logic triggers it.

BaF_2 detector is known to be a fast detector i.e. it has very short decay time. So, all the photons from a decay event is assumed to hit the PMT at the same time. A paper (opaque to photons) is covering the PMT attached with liquid scintillator, leaving only a small hole. This ensures that from a decay-event, only single photon reaches PMT. Idea behind this is that the single photon can be from anywhere in the photon emission spectrum of liquid scintillator. So, recording several of these events and obtaining the time difference between BaF_2 and liquid scintillator signal gives the overall time distribution for photons emitted by liquid scintillator for a given event. From literature, the time-profile is known to be exponential. So, fitting an exponential to the time distribution gives the decay-time of liquid scintillator.

5 Testing of the methodology

Time distribution, obtained for entire measurement, is shown in figure 5. After looking at waveforms for different time range, it is found that time delay of 200 nanoseconds(ns) and above are caused by noises only. The expanded view of time-distribution between 0 and 200 ns is shown in figure 6. The distribution between 25 ns and 175 ns is flat. It is deduced that these are caused by cosmic-ray events. Expanded view of time-distribution between -1 and 5 ns is shown in figure 7. There is rise in spectra and then exponential decay as expected. Also it is known that decay profile consists of a fast and a slow decay component. As seen from the log-plot of time

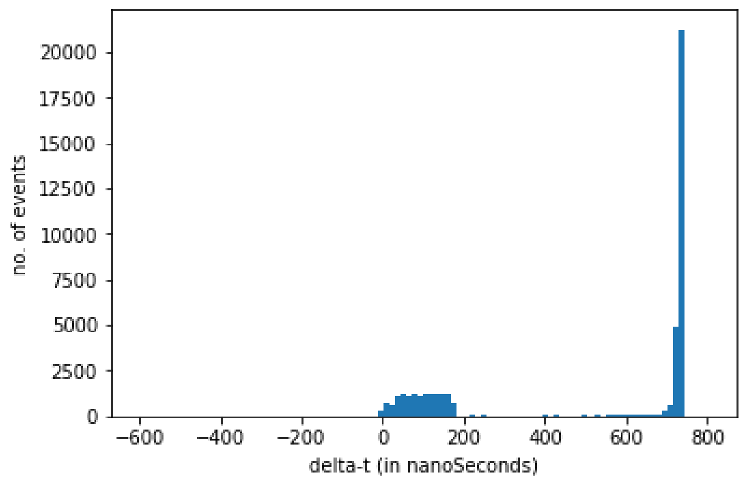

Figure 5: Time Distribution

distribution (figure 8), there are 2 slopes indicating these 2 regions.

6 Conclusions

Methodology of light yield and decay time measurement has been established. Though the uncertainty calculation is wrong for light yield measurement but it has been checked that calculation of light yield value is correct.

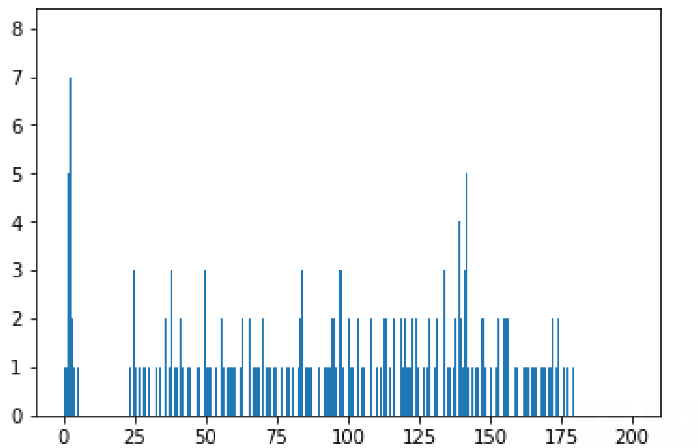

Figure 6: Time Distribution between 0 and 200 ns

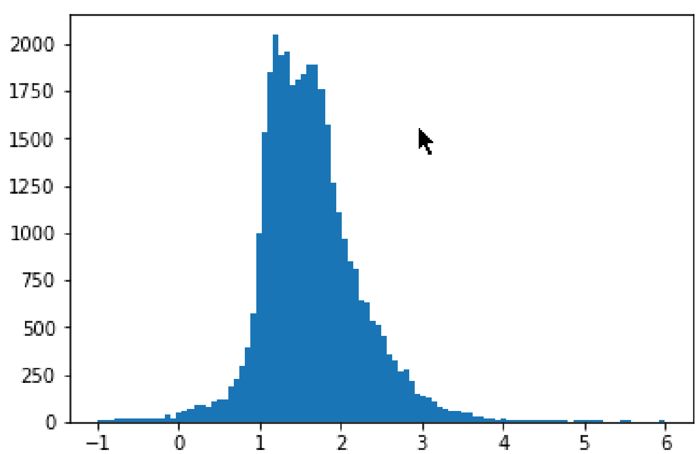

Figure 7: Time Distribution between -1 and 5 ns

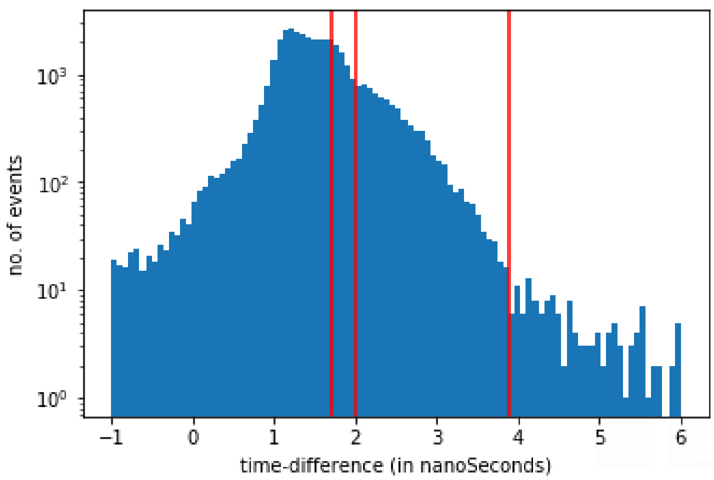

Figure 8: Time Distribution between -1 and 5 ns