RESPONSE FUNCTION STUDY FOR ENERGY TO LIGHT CONVERSION IN ORGANIC LIQUID SCINTILLATORS

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ABSTRACT

In this paper light response functions for the EJ309 liquid scintillator are developed and analyzed. Simulation results are obtained using new response functions and compared to experimental data to verify their accuracy. It is found that light response functions with a quadratic fit have negative intercepts and therefore give rise to negative light components in pulses. Although not physical, it is shown that these negative components in fact help improve the agreement between simulations and measurements. Thus, one may glean that the present values of energy deposited and light produced are over-predicting detector response which needs to be offset by the negative light components, this is especially true for low energies. To investigate this, sensitivity analysis and validation of assumptions are also performed.

I. INTRODUCTION

Detection of shielded special nuclear material (SNM) is highly important in the field of nuclear nonproliferation. The neutron energy spectrum from SNM is a signature that can be very useful in identifying and characterizing it. Most current detection systems for SNM are based on ^{3}He tubes, which detect only thermal neutrons, and therefore do not provide direct energy information. However, liquid scintillation detectors do possess the ability to detect fast neutrons and therefore maintain certain neutron energy information. Simulations are needed in order to design an effective scintillation-based measurement system; these are most commonly performed using the Monte Carlo method. However, the widely used MCNP code does not possess the ability to calculate neutron pulse height distributions such as those generated in liquid scintillators. Such distributions have been computed using specialized algorithms to process MCNPX-PoliMi outputs [1,2]. MCNPX-PoliMi's postprocessor has the ability to calculate pulse height distributions for scintillators using response functions that convert energy deposited into light produced in the detector system. Thus, it is important to carefully understand the behavior of detector light response to produce the response function. There has been work done in the past to evaluate these response functions, some of which have had negative intercepts [3]. In this paper, we will carefully study and develop response functions for a liquid scintillator in an attempt to understand the impact and significance of the negative light intercepts on detector response .

II. ENERGY TO LIGHT CONVERSION PROCESS

The EJ-309 liquid scintillator detector is comprised of hydrogen and carbon nuclei with a ratio of 1.25 to 1. Light is produced as gamma rays Compton scatter against electrons or as neutrons elastically scatter against hydrogen and carbon nuclei. The energy deposited by the gamma ray or neutron is then converted into light.

For the case of gamma rays the energy-to-light is a one-to-one conversion process. However, in the case of neutrons this process is more complicated. For neutrons, the light produced is not only a function of energy deposited but is also dependent on the nuclei on which the collisions has occurred. Furthermore, the dependence on nuclei type is also different for different nuclei. For instance in the case of carbon it has been empirically found that the energy deposited by a neutron, T, is transformed to light, L, with a rate of 2% of that for gamma rays, is converted into light [4]. Where as in the case of hydrogen, it is found the energy to light conversion can be given by the empirical formula [5]:

$$L = aT^2 + bT + c \qquad \text{Eq. 1.}$$

Here a and b are empirically found constants for the quadratic and the linear terms respectively where as c is the constant term.

Time-of-flight (TOF) measurements are used to measure these constants. In the measurement, a bare ^{252}Cf source with an activity of approximately 3×10^5 neutrons per second is placed 100 cm from the front of a cylindrical detector with a radius of 6.3 cm. Since the radius of the detector is relatively small compared to the source detector distance, one may assume that all neutrons are travelling nearly the same distance of 100 cm. Having made this assumption, one can now divide the TOF in to several narrow time bins such that each time bin corresponds to a particular energy bin of the incident neutron energy spectrum through the kinetic energy formula.

Thus, several pulse height distributions are created for these time bins. With small enough time bins these pulse height distributions correspond to quasi mono-energetic neutrons. Theoretically, the pulse heights should have a maximum value which corresponds to maximum energy deposited. In the presence of hydrogen, this will occur when a previously uncollided neutron elastic scatters against a hydrogen and transfers all of its energy. Thus ideally, the edge of the pulse height should correspond to the maximum energy deposited (i.e. the energy of the incident neutron). Hence, using the different pulse height distributions we can create pairs of energy deposited (incident energy) and light produced (edge of pulse heights). This is shown as a plot in Fig. 1.

However, with experimental data which includes noise, the edge of the pulse height is not a distinct feature and needs to be carefully determined from the measured data. For the present fit of energy-to-light conversion, as discussed in the next section, 20% of the maximum value of the pulse height distribution is chosen to be ‘the edge’. This value agrees with the edge value chosen in Ref. [6] when considering the differences in experimental setup. In the subsequent sections, we perform a sensitivity analysis of this parameter.

III. PRESENT FIT

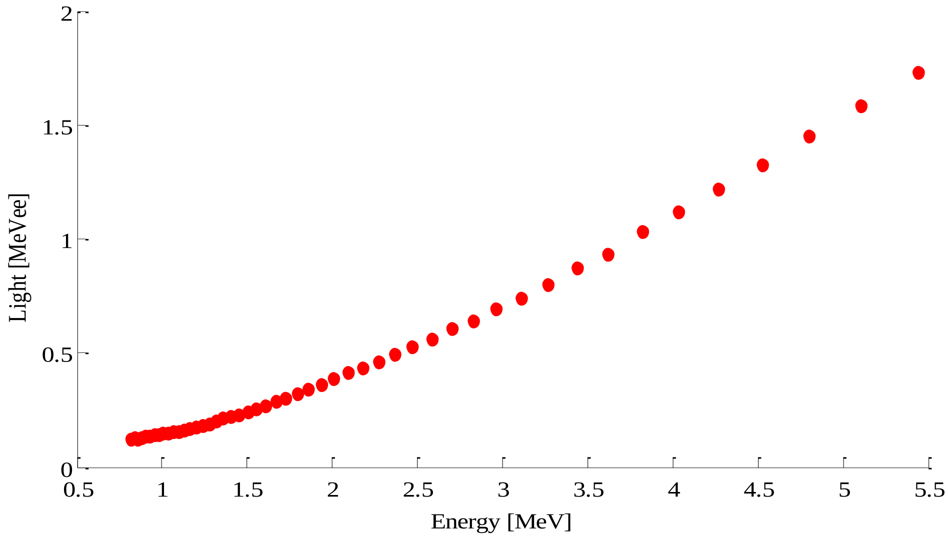

Figure 1: Energy Deposition and Light Production Curve for EJ-309

The experimental data shown above is fit to a quadratic polynomial as in Eq. 1 to yield:

$$L = 0.03495T^2 + 0.1424T - 0.0362 \qquad \text{Eq. 2.}$$

One would intuitively expect constant *c* to be zero. However, in the above equation one finds that the constant is negative. Indicating, that there is either an over prediction of light using the above curve or there is a loss mechanism that has gone unaccounted. Due to the absence of low neutron energy data the curve and should be considered valid especially in the range of neutron energies from 700 keV up to about 6 MeV. In Fig. 2 a detailed analysis is performed by simulating these pulses using an MCNPX-PoliMi data file. A pulse that is generated using the data file is a sum of several light components that fall within the pulse generation of 10 ns. The light components can be either positive or negative. The root of Eq. 2 is at 240 keV, therefore, when the energy deposited, *T*, is less than the root there will be negative light components produced. This reduces the height, or the magnitude, of the pulse and thus in the pulse height distribution the counts will move towards lower light bins. This can also push some pulses below the threshold value of 70 keVee, thereby, reducing total number of counts in the entire pulse height spectrum.

In Fig. 2a for pulse whose net pulse height (including the negative light components) are greater than the threshold, reduction factor in their magnitude due to negative light contribution is calculated and averaged over 30 keVee bins. The total positive light sum is plotted on the x-axis and the reduction in the total positive sum due to negative light is plotted on the y-axis. It is evident that for pulse heights between approximately 100 keVee and 500 keVee the reduction in pulse height magnitude can be as large as 10-15%. Furthermore, there are nearly 75% of pulses with total positive light output in this range of 100 keVee to 500 keVee. This can be gleaned from Fig. 2b that shows the probability of occurrence for a pulse whose total positive light is known. In Fig. 2b points are placed at the center of light bins that are a 100 keVee wide.

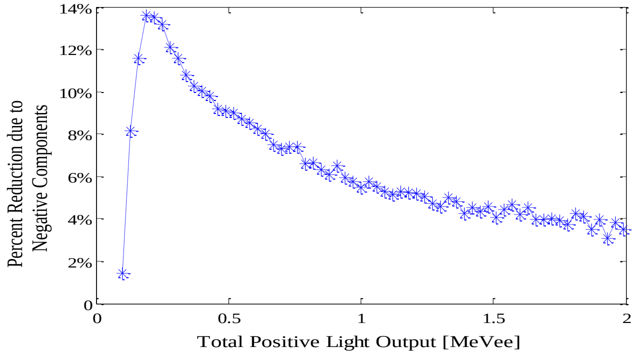

Figure 2a: Reduction of simulated pulse heights due to low energy collisions that generate negative light averaged over 30 keVee bins.

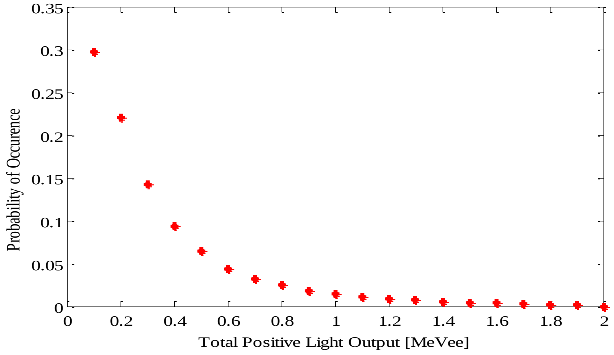

Figure 2b: Probability of occurrence for total positive light pulse for 100 keVee bins.

A comparison of measured and simulated neutron pulse height distribution for a bare ^{252}Cf source at distance of 30 cm from the scintillator is shown in Fig. 3. Here, Eq. 2 with the negative intercept has been used to simulate Fig. 3a, while, Fig. 3b has been generated with a zero intercept. Fig. 3b over-predicts in the same region (100 keVee to 500 keVee) where Eq. 2 would produce significant negative light components as illustrated in Fig. 2 since there is negative light produced in this case. The impact of Fig 2 is seen by comparing Fig 3a and 3b: the negative light contributions act upon the excess light to give better agreement in the case of Fig. 3a.

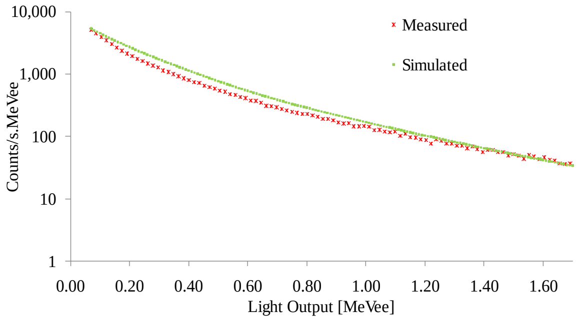

Figure 3a: ^{252}Cf simulation with negative intercept

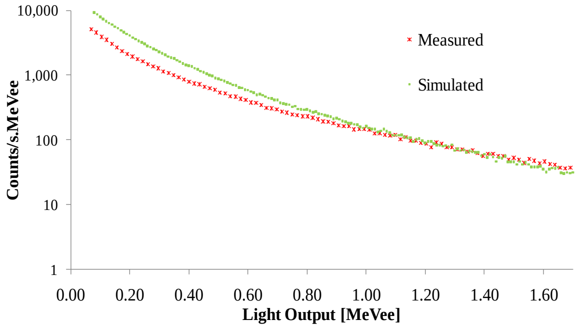

Figure 3b: ^{252}Cf simulation with zero intercept

Thus from the above analysis it is clear that there is a need to systematically find factors that can help reduce excess light production in the region 100 keVee to 500 keVee. This range as seen in Fig. 1 corresponds to low energies up to about 2 MeV. In the following section we will try to explore factors that can affect the fit shown in Fig. 1 to eliminate the negative intercept such that the energy to light conversion coefficients do not produce nonphysical light components and yet give a good agreement between measured and simulated results.

IV. SENSITIVITY ANALYSIS

As discussed at the end of Sec. II, the determination of the edge of a measured pulse height distribution of a nearly monoenergetic case is not simple since it is distorted by noise and measurement uncertainties. In our analysis a value of 20% of maximum is chosen as the edge. Thus, we try to vary this percentage of the edge value to find the impact on simulated pulse height distributions. Furthermore, the distance that the neutrons travel is also increased to include interaction depths since neutrons travel a certain distance in the detector before depositing their energies. Next, we investigate the impact of changing the ^{137}Cs calibration to determine the amount of light produced from the charge recorded.

a) Varying Edge Values and Interaction Depth

The edge values were calculated at 20% and 50% of the maximum for neutron flight paths corresponding to the face of the detector and repeated for an interaction depth of 4 cm inside the detector. There are some noticeable trends: making variations does not impact the distribution in the low light output bins as much as for higher light output bins. As the edge values are increased from 20% to 50%, for a given interaction depth, the neutron pulse height distributions are reduced for higher light outputs. As interaction depth is increased the pulse heights distribution are also reduced.

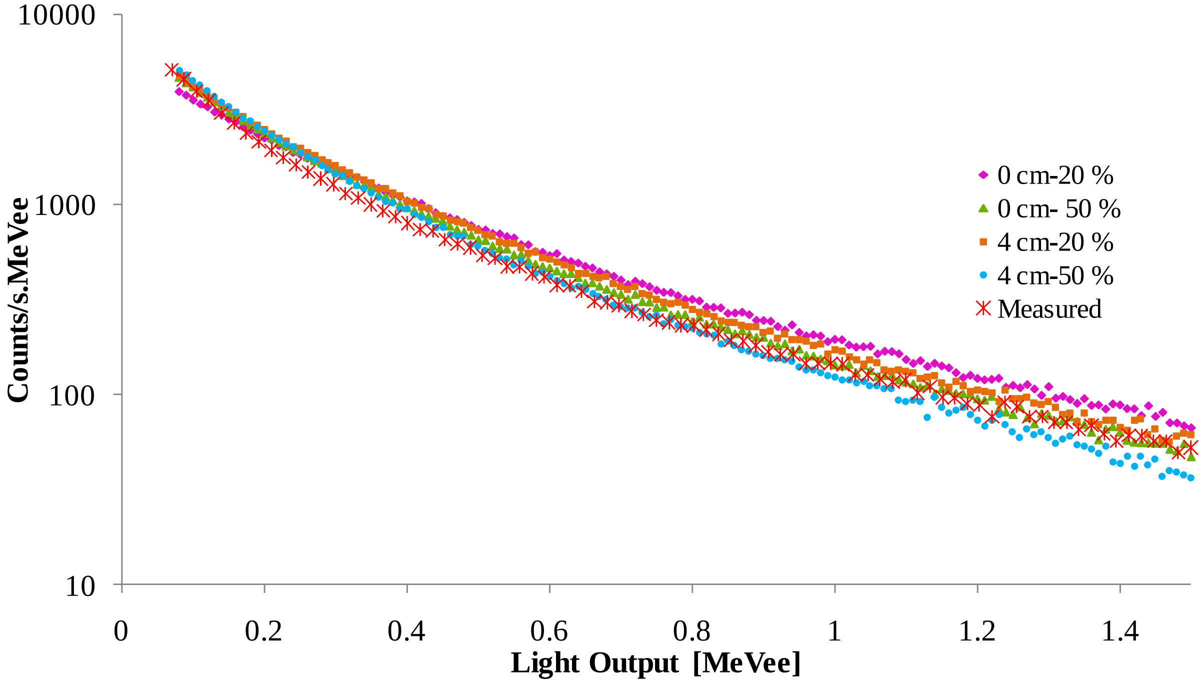

Figure 4: Pulse height distributions for bare ^{252}Cf for varying edge values and interaction depth

The constants *a*, *b* and *c* as shown in Eq. 1 have been provided in Table I for the cases plotted above. Table I shows that the intercepts, *c* tend to become less negative as we move the edge value higher up.

Table I: Coefficients for Varying Depth and Edge Value

Case	*a*	*b*	*c*
0 cm – 20%	0.048448	0.17849	-0.061007
0 cm – 50%	0.042940	0.13635	-0.043883
4 cm – 20%	0.045067	0.14741	-0.043161
4 cm – 50%	0.037450	0.12096	-0.036679

b) Varying ^{137}Cs Calibration to Determine Light Production

The ^{137}Cs calibration is performed to convert the charge recorded into light produced. It is done by estimating the Compton edge of the ^{137}Cs spectrum as a feature that occurs at 75% of the maximum. Other studies have also looked at this value which typically falls within the range of 60% to 90% [7].

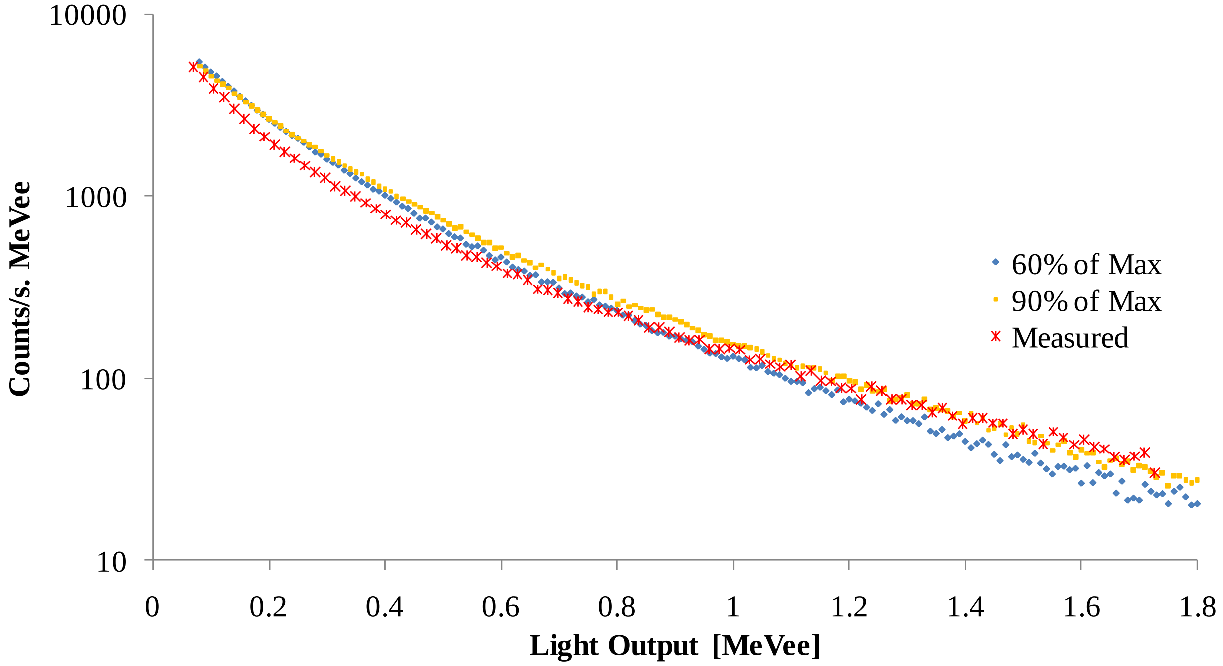

Figure 5: Pulse height distributions for bare ^{252}Cf by varying the Compton edge in ^{137}Cs calibration

Thus, if we move the edge to the right or higher voltage it would indicate more light produced at a given energy, similarly shifting it to the left indicates less light produced. This is can be understood from the comparisons in Fig. 5 and coefficients listed in Table II for the quadratic Eq. 1. The coefficients in Table II are higher for the case of 90% of maximum taken for ^{137}Cs calibration and thus it would lead to greater light production despite the slightly more negative intercept. This can be verified when we notice that in Fig. 5 the simulation of pulse height distribution using 90% of maximum as the Compton edge has higher counts than the simulation using 60% of maximum.

Table II Coefficients for varying Cs Edge

Case	***a***	***b***	***c***
60 % max Compton edge	0.0326	0.1335	-0.0337
90 % max Compton edge	0.0368	0.1506	-0.0380

V. VALIDITY OF ASSUMPTIONS

We have made some assumptions in the process of evaluating energy deposited and light produced. When thin TOF slices are taken to correspond to certain energies it is possible that these TOF slices also captures some of the neutrons from adjacent energy bins. For instance, a given time-slice corresponding to a certain energy bin can get contribution from a higher energy neutron that interacts deep in the detector and thus travel a greater distance than the assumed TOF distance. The actual distributions are simulated using MCNPX-PoliMi data file as shown in Fig.6.

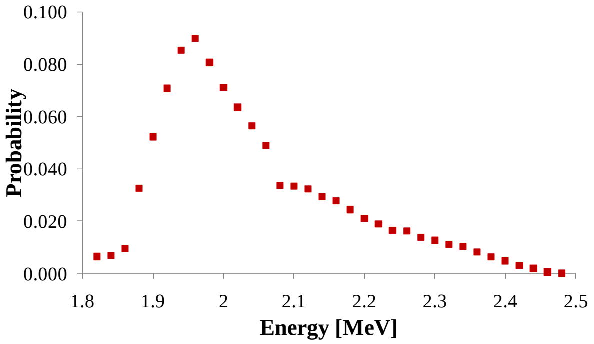

Figure 6a: Distribution of contributing energies for the time window corresponding to 1.95 MeV – 2.05 MeV energy bin.

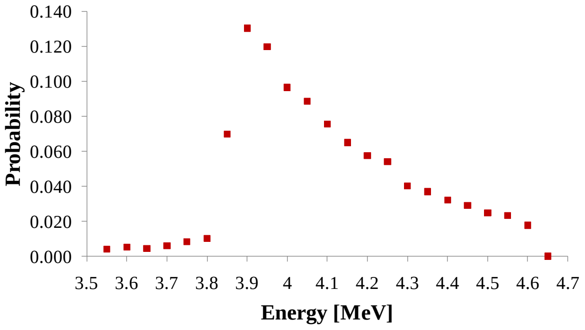

Figure 6b: Distribution of contributing energies for the time window corresponding to 3.95 MeV – 4.05 MeV energy bin.

VI. CONCLUSION

In this paper, we have explored light response functions that enable us to simulate response of the EJ309 liquid scintillator detector. It is found that a quadratic fit gives good results. However, it has a negative intercept which affects the low energy region that is outside of the empirical fit. Negative light contribution to the light pulses are analyzed, and as seen in Fig, 2 & 3, it is concluded that negative light contribution significantly affects and reduces the pulse heights between a 100 keVee and 500 keVee. Pulses of this magnitude are produced by energy deposition of less than 2 MeV as seen in Fig. 1. It is also shown that the negative intercept is in fact needed to reduce the pulse heights in order to better match measurement results. Therefore, we conclude that our model is over predicting the response of neutrons with less than 2 MeV of energy that is being compensated for by these negative light contributions.

Furthermore, sensitivity analyses are performed on various parameters, such as ^{137}Cs Compton edge calibration and interaction depth, to analyze impact on simulations. It is shown that as the Compton edge for the ^{137}Cs calibration is moved to higher percentages of the maximum, pulse heights are increased. It is also observed that for greater interaction depths and higher fraction of maximum taken as the edge value, the pulse heights distributions have decreased counts at higher light output bins. Finally, the assumptions made in the process are carefully analyzed to determine their limitations and impact on our present analyses. In the future, we will continue this work guided by the conclusions drawn here to find a response function that will not only yield good agreement between measurement and simulations, but will also eliminate the need of negative light contributions.

VII. REFERENCES

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