Measurement of scintillation light yield in NaI(Tl) detector for the SABRE dark matter experiment

Md. Shahinur Rahman\(^{1,2}\), Lindsey Bignell\(^2\), Wayne D. Hutchison\(^1\), Heiko Timmers\(^1\) and Gregory Lane\(^2\)

\(^1\)School of Science, The University of New South Wales (UNSW), Canberra, ACT, Australia
\(^2\)Department of Nuclear Physics, The Australian National University, Canberra, ACT, Australia

I. INTRODUCTION

Scintillation detectors have numerous applications in nuclear science, experimental particle physics, medical physics, environmental studies and many other areas [1], [2]. The high light output, optimum energy resolution, standard light yield proportionality and lower production costs are the prerequisite for the scintillation materials to make a good scintillation detector [1], [3], [4], [5], [6]. The development of inorganic and organic scintillation detectors has been tried over the past few decades due to different industrial and research applications [6], [7], [8], [9]. Plastic scintillators are used for neutrons and charged particles detection and spectroscopic applications although its light output is lower than most of the inorganic scintillation detectors due to lower fabrication cost, fast decay time of light pulse and easy to use. In 1948 NaI(Tl) inorganic scintillation crystal was discovered and it is being widely used and most known scintillation crystal to make scintillation detectors with high light output and energy resolution [7], [8], [9]. To understand the scintillation process in NaI(Tl) scintillation detector over the past few decades, significant amount of research has been carried out across the world; however, many aspects of NaI(Tl) detector are not fully understood to date [7], [8], [9]. A major complication in NaI(Tl) detector is that the proportionality between the incident particle energy and the number of photons generated, known as the scintillation light yields, is not always constant. In NaI(Tl) detector there is a well-known non-linearity for gamma ray photons and electrons production depending on energy deposition in scintillation crystal, which could affect the energy resolution and scintillation efficiency of NaI(Tl) detector. In the case of heavy charged particles recoiling in Na (sodium) or I (Iodine) nuclei of scintillation crystal, the scintillation light yields are only a small fraction of that for electrons or photons productions inside the scintillation crystal [1]. In dark matter detection experiment, dark matter signals result from the recoil of either sodium or iodine nuclei in the scintillation crystal [4], SABRE (Sodium-Iodide with Active Background Rejection) dark matter experiment based on NaI(Tl) scintillation detectors will be operated in southern (Staywell Underground Physics Laboratory, Melbourne, Australia) and northern hemisphere (INFN, Italy) simultaneously for 3-5 years to verify the DAMA/LIBRA dark matter detection claim [4]. Therefore, it is imperative to know the light yield non-proportionality in NaI(Tl) crystal and quenching factor of Na and I nuclei recoils. Light yield non-proportionality can be measured in NaI(Tl) detector as a function of either electron response or photon response [8]. Electron response is the ratio of light yield to the energy of electron and it is an intrinsic characteristic of scintillating material like NaI(Tl). Porter et al. have studied the electron response non-proportionality of different scintillation detectors with external electron source, which could be affected by surface effects in scintillation materials [8]. Rooney et al. and Valentine et al. have introduced the Compton coincidence technique (CCT) to measure the light yield non-proportionality in NaI(Tl) detector [7]. The Compton coincidence technique can measure the electron response in the range 3-450 keV more accurately because the monoenergetic electrons are produced inside the scintillation crystal by γ ray energy deposition in the NaI(Tl) scintillator [7], [8].

The main aim of this study was to investigate the light yield non-proportionality in NaI(Tl) detector as a function of electron response for SABRE dark matter experiment.

II. EXPERIMENTAL METHOD

In the conducted CCT experiment shown in Fig. 1, a 662 keV \(^{137}\)Cs (10 µCi) radioisotope was used as γ-rays energy source with close proximity to NaI(Tl) detector to measure the electron response in the scintillation material of NaI(Tl) detector as a function of electron energy. The position of \(^{137}\)Cs gamma source close to the NaI(Tl) detector was varied from 30° to 135° for understanding the Compton scattered gamma photon energy deposition in HPGe (High Purity Germanium) detector. The NaI(Tl) (905-3, 2 x 2 inches crystal, 2 inches tube) and HPGe detectors were purchased from ORTEC, USA for this study. All used detectors and gamma source for CCT experimental set up were mounted on a circular stage to facilitate the position change of \(^{137}\)Cs radioisotope. In the conducted CCT experiment, 12 different scattering angles were selected to collect the HPGe (Compton scattered energy) and NaI(Tl) (recoil electron energy) spectra, which was finally used to calculate the scintillation light yield non-proportionality. The schematic of the nuclear
The energy of scattered photon ($E_{sc}$) can be calculated by [8],

$$E_{sc} = \frac{E_{in}}{1 + \frac{E_{in}}{m_0c^2}(1 - \cos \theta_{sc})} \quad (1)$$

In the Fig. 1 and Eq. 1, $E_{in}$ is the incident photon energy, $E_{sc}$ is scattered photon energy, electron rest mass energy ($m_0c^2$) is equal to 511 keV, $\phi$ is electron recoil angle and $\theta_{sc}$ is the Compton scattering angle. In fact, the probability of Compton scattering at an angle can be estimated from the Klein-Nishina equation [4].

III. RESULTS AND DISCUSSION

Fig. 2 shows the energy spectrum of $^{137}$Cs radioisotope source which was used to calibrate the NaI (Tl) detector, when the energy resolution was around 9.5%. The energy calibration was also done for HPGe detector. To understand the relationship between channel number and energy (keV) for both of the detectors, energy calibrations were conducted using $^{137}$Cs and $^{133}$Ba radioisotopes. Energy spectra from NaI(Tl) detector based on CCT were fitted with user defined Gaussian-Step function and ORTEC MCA software, and then mean recoil electron energy was calculated using detector’s calibration data. In addition, the energy spectra from HPGe detector was fitted with Gaussian function only. The energy response for both of the detectors in CCT at Compton scattering angle 30° is shown in Fig. 3. The recoil electron energy in NaI(Tl) detector is increasing with increasing the Compton scattering angle shown in Fig. 4, which is opposite to the scattered energy deposition in HPGe detector. The obtained electron recoil energy ($E_e$) from NaI(Tl) detector with FWHM according to MCA software fit and Compton scattering angle is given in Table 1. The recoil electron energy deposition in NaI(Tl) detector at scattering angle 90, 100 and 110° shows relative inconsistency with overall energy deposition trend due to detector’s less energy resolution and photomultiplier noise effects, because the NaI(Tl) detector’s energy resolution usually decreases with increasing the electron energy in CCT and the photomultiplier signal can be affected by heating effects [1], [7], [8], [9]. The total energy response of NaI(Tl) detector in CCT depends on geometric component and electron energy resolution subtended by the HPGe detector. The total energy response from NaI(Tl) and HPGe detectors in CCT was not equal to the 662 keV $^{137}$Cs γ-rays value always, which might be due to the detectors geometric component and data acquisition system [8].
Figure 2. Energy spectrum of 662 keV γ-rays from 137Cs radioisotope source measured with NaI(Tl) detector for calibration purpose.

Figure 3. The energy spectra at 30° scattering angle in CCT with fitting: (a) recoil electron energy peak from NaI(Tl) detector, and (b) Compton scattered energy peak from HPGe detector.

Table 1: Mean recoil electron energy from MCA software fit with FWHM at different scattering angle.

<table>
<thead>
<tr>
<th>Compton scattering angle (Degree)</th>
<th>FWHM in channel number</th>
<th>Electron recoil energy (E_e) in NaI(Tl) in keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>24.72±1.4</td>
<td>94.934</td>
</tr>
<tr>
<td>40</td>
<td>26.540±0.91</td>
<td>129.350</td>
</tr>
<tr>
<td>50</td>
<td>34.73±0.62</td>
<td>190.92</td>
</tr>
<tr>
<td>60</td>
<td>36.47±1.1</td>
<td>214.68</td>
</tr>
<tr>
<td>70</td>
<td>35.65±1.3</td>
<td>286.09</td>
</tr>
<tr>
<td>80</td>
<td>37.67±1.1</td>
<td>323.340</td>
</tr>
<tr>
<td>90</td>
<td>33.79±1.4</td>
<td>294.626</td>
</tr>
<tr>
<td>100</td>
<td>33.35±1.6</td>
<td>385.805</td>
</tr>
<tr>
<td>110</td>
<td>45.67±1.4</td>
<td>369.85</td>
</tr>
<tr>
<td>120</td>
<td>46.36±1.5</td>
<td>406.27</td>
</tr>
<tr>
<td>130</td>
<td>48.86±1.7</td>
<td>415.321</td>
</tr>
<tr>
<td>135</td>
<td>54.16±2.5</td>
<td>423.60</td>
</tr>
</tbody>
</table>
The total energy response in CCT can also be affected with HPGe detector’s energy calibration data, which could result in incorrect Compton scattered energy deposition value [10]. In addition, multiple Compton scattering in scintillator can also increase the systematic error for measuring the total amount of energy deposited in scintillator based on CCT. The electron response or relative light yield in NaI(Tl) detector using CCT measurement was calculated as the ratio of detected electron recoil energy ($E_{NaI(Tl)}$) in the NaI (Tl) detector and the actual recoil electron energy ($662 \text{ keV} - E_{HPGe}$). The electron response,

$$R = \frac{E_{NaI(Tl)}}{662 \text{ keV} - E_{HPGe}} \quad (2)$$

The R was plotted in Y-axis as a function of the actual recoil electron energy (X-axis) shown in Fig. 5. All the four curves for electron response as a function of electron energy was normalized at 440 keV to compare with each other precisely.

Calculated electron response based on conducted CCT experiment shown in Fig. 5 is well agreed with previously published results, which confirms that the CCT is providing the accurate measurement for relative light yield non-proportionality of NaI(Tl) detector within the experimental uncertainty [2], [7], [8], [9]. In Fig. 5, the calculated results indicate a nearly proportional electron response above 150 keV (3.5% change). Below 150 keV, the electron response increases more significantly, indicating a higher light yield nonproportionality for the low electron energy.

The higher light yield nonproportionality at low electron energy in NaI(Tl) scintillator could be due to the non-uniform ionization density, photomultiplier thermal noise, scintillator size and crystal quality. With the state-of-the-art electronics and detectors, more accurate measurement of light yield non-proportionality of ultrapure NaI(Tl) crystal in CCT could be achieved in the electron energy range 2 – 450 keV. Another CCT based light yield nonproportionality measurement in ultrapure NaI(Tl) scintillator will be carried out at 5°, 10° and 15° Compton scattering angles with higher energy γ-rays source for understanding the electron response at low electron energy. In conclusion, the light yield nonproportionality data obtained will be useful for the SABRE dark matter experiment.

![Figure 5. Relative light yield response in NaI(Tl) detector versus electron energy using CCT normalized at 440 keV arbitrarily.](image)

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REFERENCES

5. M. Gierlik, “Comparative Study of Large NaI(Tl) and BGO Scintillators for the EURopean Illicit TRAfficking Countermeasures Kit Project”.