Measured response of a liquid scintillation detector to quasi-monoenergetic electrons and neutrons

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Abstract: The response of a liquid scintillator (EJ-301) to monoenergetic electrons tagged by Compton back scattered $\gamma$-rays has been measured using various radioactive $\gamma$-ray sources. It is observed that the measured electron response is linear up to an energy of $\sim 4$ MeV. The resolution of the liquid scintillator at an energy 1 MeVee is found to be $\sim 11\%$. The pulse shape discrimination and pulse height response of the liquid scintillator for neutrons have been measured using the $^7$Li(p,n)$^7$Be*(0.429 MeV) reaction. A nonlinear response to mono-energetic neutrons for the liquid scintillator is observed at energies $E_n=5.3$ MeV, 9.0 MeV and 12.7 MeV. In addition, the measured response of the liquid scintillator for electrons and neutrons has been compared with simulated results obtained using the Monte Carlo based Geant4 toolkit.

Keywords: Neutron detectors (cold, thermal, fast neutrons); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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1 Introduction

The measurement of the neutron energy spectrum is useful for the study of the thermodynamic properties of excited compound nuclei and also have applications in nuclear energy production based on fusion and fission reactions. The interaction of neutrons with matter, useful in their detection, leads the production of secondary charged particles through nuclear reactions. Transfer of a substantial fraction of fast neutron energy by scattering off a light nucleus is the most common mechanism for the fast neutron detection. Hydrogenous materials *viz.* plastic and liquid scintillators are used for fast neutron measurement and detection [1]. The fast component of the scintillation light of the detector is used for timing measurement, while both fast and slow components are used for discriminating neutrons from $\gamma$-rays on the basis of pulse shape discrimination (PSD). Plastic scintillators offer very good timing information and therefore are used for neutron measurements employing time of flight technique [2], whereas the liquid scintillators (LS) have both PSD and very good timing properties [1]. A recently developed plastic scintillator also shows pulse shape discrimination of neutrons against $\gamma$-rays [3]. A comparison of measured PSD between EJ299-33 plastic scintillator and EJ309 liquid scintillator [4] of the same size shows that EJ309 has a better figure of merit for PSD than EJ299-33 at the same measurement threshold [5]. The measurement of PSD for same size scintillators, such as EJ-301, EJ-309 (both LS) and EJ299-33 (plastic), shows that the EJ-301 has relatively the best figure of merit for neutron and $\gamma$ rays discrimination at same threshold [6] among those scintillators.

A mini array of 18 liquid scintillators has been set up for fast neutron spectroscopy at the Pelletron-LINAC Facility (PLF), Mumbai. The set up will be extended to an array of 80 liquid
scintillators (EJ-301) to measure neutron cross sections as low as \( \sim 1 \mu b/sr \) and will complement the existing array of plastic scintillators [2]. The setup will be useful for the study of washing out of shell effect [7] and damping of rotational enhancement of nuclear level density with excitation energies, the measurement of the prompt fission neutron spectrum in the fast neutron induced fission of actinides, neutron multiplicity for the study of fusion-fission dynamics and for other measurements involving neutrons.

In this paper, we report results of the measured response of a representative liquid scintillation detector as well as the layout of the mini array of LS. The paper is organized in the following sections. The details of the mini array are given in section 2. The subsequent section describes detector response to electrons. The TOF, PSD and pulse height response to mono energetic neutrons measured using the \(^7\text{Li}(p,n)^7\text{Be}^* (0.429\text{MeV})\) reaction at proton energies from 8 MeV to 16 MeV are given in section 4. Then, a comparison of the results with Geant4 simulation is presented in section 5 and followed by summary of the present work.

2 Details of the scintillator array

A mini array of 18 liquid scintillators (LS) has been set up for the study of fast neutron spectroscopy in the energy range from 0.5 MeV to 20 MeV by pulse shape discrimination and time of flight technique (TOF). Each of the LS (equivalent to NE213 and procured from SCIONIX, Holland) is cylindrical in shape with 12.7 cm diameter and 5 cm thickness [8]. The scintillator has a light output of \( \sim 78\% \) compared to that of anthracene and a bulk attenuation length \( >2.5\text{ m} \). The mean scintillation decay times of the scintillator are \( \sim 3.2\text{ ns} \) (fast), 32.3 ns and 270 ns (slow). Each LS is coupled to a fast, linear focused, 12.7 cm diameter Hamamatsu R1250 (14 stage) photo-multiplier tube (PMT) for signal readout. The detector with a special designed window ensures 100\% hermetic seal and can be used in all orientations. The scintillator has a carbon to hydrogen ratio of \( \sim 1:1.2\) and refractive index of 1.5. The spectral sensitivity of the PMT peaks at 420 nm, with a quantum efficiency of \( \sim 22\% \), and matches the emission spectrum of the liquid scintillator. The PMT has a fast response time (rise time \( \sim 1.3\text{ ns} \)) and a gain of \( \sim 10^7 \) at about 2 kV bias voltage. The PMTs are powered by a 48 channel programmable high voltage power supply developed in-house similar to one of ref. [9]. These scintillators are mounted on a mechanical stand, placed at a flight path of
Figure 2. Schematic of the experimental setup for Compton back scattered γ-ray tagged electron for the measurement of liquid scintillator response to electrons.

Figure 3. Comparison between recoil electron spectra of the LS obtained from singles measurement (green dashed line) and coincidence measurement (red line) with back scattered γ-rays using $^{60}$Co source.

75 cm with an angular separation of 16° among the detectors. Figure 1 shows a photograph of the mini array of LS displaying the aluminum cells for liquid scintillator and the PMTs with mu-metal shield. Each aluminum cell can accommodate about 5% volume expansion of the liquid scintillator. The anode signal of each LS is processed for generating the fast timing signal using a constant fraction discrimination (CFD) and for deriving the energy and the PSD applying a Mesytech MPD4 electronics module. The data are stored using a multi-parameter VME based data acquisition system and offline analysis carried out with the Linux Advanced MultiParameter System (LAMPS) [10].

3 Response of the liquid scintillator (LS) to electrons

Liquid scintillation detectors are used for fast neutron spectroscopy as they offer a fast timing response and excellent PSD for neutron and gamma separation. The knowledge of absolute detection efficiency is essential for the measurement of neutron cross section. However the neutron detection efficiency is a function of energy and its detection threshold. The determination of the detection threshold depends on how calibration is done. The organic scintillation detectors are normally calibrated using Compton edge of the γ ray spectrum. This method introduces error while selecting
Figure 4. Pulse height response of liquid scintillator up to \(\sim 4\)MeV electron equivalent energy using \(^{22}\)Na, \(^{137}\)Cs, \(^{60}\)Co and \(^{241}\)Am-\(^{9}\)Be sources.

the Compton edge as the measured spectrum is smeared by finite detector resolution and its nonlinear light output. The accurate and precise calibration of the LS can be made using a coincidence method between Compton back scattered \(\gamma\)-rays and the recoil electron [2, 11]. The energy calibration obtained are expressed in the scale of electron energy equivalent (\(E_{ee}\)).

3.1 Experimental details

A coincidence experiment has been carried out using a LS belonging to the scintillator array and a BaF\(_2\) detector for the study of the LS response to electrons using \(^{137}\)Cs, \(^{22}\)Na, \(^{60}\)Co and Am-Be radioactive sources. A schematic the experimental setup for this measurement is shown in figure 2. The BaF\(_2\) detector has hexagonal cross section with \(\sim 6\) cm side to side distance and thickness of 8 cm. For the measurements of pulse height response, the \(\gamma\)-rays were collimated using 2” thick Pb bricks. The Compton scattered \(\gamma\)-rays from the LS are detected by the BaF\(_2\) detector placed at \(\theta \sim 125^\circ\) with respect to the incident direction. The energy of the recoil electron (\(E_e\)) depends on the scattering angle and is given by, \(E_e = \frac{\alpha E_\gamma (1-\cos \theta)}{1+\alpha (1-\cos \theta)}\), where \(\alpha = E_\gamma / m_e c^2\). The anode signal from the LS has been split into two parts, one part is fed to a constant fraction discriminator (CFD) for the TOF measurement. The other one is sent to a Mesytec MPD4 for the pulse height and the pulse shape discrimination (PSD) information. The anode signal of the BaF\(_2\) detector is send to the CFD for generating the start signal for a time to amplitude converter to measure the TOF spectrum. The dynode signal from the BaF\(_2\) detector has been fed to a spectroscopic amplifier for obtaining the energy of back scattered \(\gamma\)-rays. A coincidence between the LS and BaF\(_2\) detector has been used as the master trigger. The parameters, such as energy signal of the BaF\(_2\) detector, the LS energy, PSD and TOF with respect to the BaF\(_2\) detector were recorded in an event-by-event mode using a VME based data acquisition system.
3.2 Results and discussion

The recoil electron spectra are shown in figure 3 obtained for $^{60}$Co source. It is observed that the singles measurement shows only Compton continuum due to 1.17 MeV and 1.33 MeV $\gamma$-rays. However, the coincidence measurement between the recoil electron and the back scattered $\gamma$-ray shows two well resolved peaks at energies 0.9 MeV and 1.1 MeV. These well resolved peaks can be used for precise energy calibration of the LS instead of employing Compton edge for the same purpose. The coincidence measurement has been performed for electron response in the energy range from $\sim$0.3 MeV to 4.1 MeV using radioactive sources. The typical pulse height spectra are shown in figure 4. The peak positions are plotted against the corresponding recoil electron energy shown in figure 5. It shows a linear behavior up to energy of 4.1 MeV. However, the measurement carried out by Swiderski et al. using wide angle Compton coincidence technique shows the nonlinear behaviour down to very low energy (10 keV). The non-proportionality of light output found to be $\pm$6% in the energy range from 0.3 MeV to 4.1 MeV which is close to the reported values [12]. In this measurement, the resolution of the LS is found to be 11% at $\sim$1 MeVee (MeV electron equivalent). The detector resolution has been measured at 0.3, 0.4, 1.0 and 4.1 MeV and the energy dependent resolution is plotted in figure 6. The energy resolution of the LS is fitted with $f(E_{ee}) = \sqrt{a^2 + \frac{b^2}{E_{ee}} + \frac{c^2}{E_{ee}^2}}$, where $a$, $b$ and $c$ are fitting parameters. The resolution function is an important input for the Monte Carlo simulation to estimate the neutron detection efficiency.

4 Response of the LS to neutrons

4.1 Experimental details

The experiment has been performed with proton beam of energies 8 MeV, 12 MeV and 16 MeV to produce mono-energetic neutrons in $^7$Li(p,n)$^7$Be reaction at the PLF, Mumbai. Neutrons were measured in coincidence with 429 keV $\gamma$-rays coming from the excited $^7$Be. A simplistic representation of neutron production in $^7$Li(p,n)$^7$Be reaction along with a schematic experimental set up are shown in figure 7. A LS detector is placed at a distance of 1 m from the target and at an
Figure 6. Energy resolution of the LS as a function of energy and fitted with resolution function $f(E_{ee}) = \sqrt{a^2 + b^2/E_{ee} + c^2/E_{ee}^2}$, where $a$, $b$ and $c$ are fitting parameters.

Figure 7. (a) A schematic the experimental setup for the measurement of the liquid scintillator response to fast neutrons, and (b) simplified representation of neutron emission in $^7$Li(p,n)$^7$Be reaction.

angle of 45° with respect to the beam direction. An array of seven closely-packed hexagonal BaF$_2$ detectors is placed close (~3 cm) to the target for detecting the $\gamma$-rays. A block diagram of the electronics used for this measurement is shown in figure 8. The anode signal of the LS was split into two parts, one part was fed to a constant fraction discriminator (CFD) for the time measurement (T_LS). The other one was sent to a Mesytec MPD4 for the pulse height measurement and the pulse shape discrimination information by measuring the zero cross over time (ZCT) in reference to CFD, expressed by the internal time to amplitude converter (TAC) of MPD4. The dynode signal from BaF$_2$ detectors was sent to the amplifier (AMP) through the preamplifier (PA) to measure the energy of gamma rays. The anode signals were sent to the CFD to generate the time signals of the BaF$_2$ detectors (TB). All the TB signals were time matched using a variable delay (DV8000) module and generated a logic OR of BaF$_2$ signals (T_BaF2) which was used as a start of a TAC for the TOF measurement. The coincidence between the LS and BaF$_2$ was used as the master trigger. The threshold of the CFD was put at ~125 keVee. The ZCT, energy deposited in the LS, TOF with respect to the BaF$_2$ array and energies of BaF$_2$ detectors were recorded in an event by event mode.
Figure 8. A block diagram of the electronics used for the measurement of the LS response to neutron using $^7$Li(p,n)$^7$Be reaction. The energy of BaF$_2$, TOF, energy and ZCT of LS are sent to VME ADC for data acquisition.

Figure 9. A two dimensional (2D) plot of the measured ZCT and the energy ($E_{ee}$) for the discrimination of neutron and $\gamma$-ray events in the (p,n$_1$) reaction at $E_p=8$ MeV.

The TOF was calibrated using a high precision time calibrator. The energy calibration of the LS has been performed by measuring the energy of the electrons tagged by the Compton back scattered $\gamma$-rays which were detected in a NaI(Tl) detector.

4.2 Results and discussion

A two dimensional plot of the measured ZCT and energy is shown in figure 9. It is observed that the LS has very good discrimination of neutrons from $\gamma$-rays. The quantitative description of the
Figure 10. Measured neutron TOF spectra at various beam energies for the target to detector distance of 1 m. The neutrons peaks in the TOF spectra for corresponding proton beam are well separated from $\gamma$ rays.

Figure 11. Measured pulse height responses of the liquid scintillator at $E_n=5.3, 9, 12.7$ MeV using $(p,n_1)$ reaction.

PSD is given by the figure of merit (M) which is defined as the ratio of individual peak separation to the sum of their full widths at half maximum (FWHM) at a given threshold. In this measurement, the figure of merit $M \sim 1.8$ has been obtained at a threshold of 1 MeVee. This result compares with neutron-gamma discrimination capability of the liquid scintillator (EJ-301) measured by D. Cester et al. using $^{252}$Cf source [6]. The TOF spectra for neutrons have been measured in coincidence with 429 keV $\gamma$ rays are shown in figure 10. The neutron peaks are well separated from the $\gamma$ rays in the TOF spectrum. The measured neutron energies ($E_n^{\text{Meas}}$) deduced from the TOF spectra are tabulated in table 1 and show a good agreement with kinematics. The measured pulse height spectrum of LS has been extracted using suitable prompt neutron gate in TOF spectrum and the background pulse height spectrum has been obtained for the same time window excluding neutron and gamma peaks.
Table 1. Measured neutron energies ($E_{\text{Meas}}$) deduced from the TOF spectra and calculated $E_{ee}$ using the empirical relations [13–16] for various proton energy ($E_p$) in the (p,n$_1$) reaction. $E_{\text{Kin}}^n$ is the neutron energy calculated using 2 body kinematics for $^7$Li(p,n$^1$)Be reaction at $\theta = 45^\circ$. $E_{\text{end}}$ is the end point energy of the measured pulse height spectrum in figure 11. All the figures in the table are in the units of MeV.

| $E_p$ (MeV) | $E_{\text{Kin}}^n$ (MeV) | $E_{\text{Meas}}$ (MeV) | $E_{\text{end}}$ [13] (MeV) | $E_{ee}$ [13] (MeV) | $E_{ee}$ [14] (MeV) | $E_{ee}$ [15] (MeV) | $E_{ee}$ [16] (MeV) |
|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 8.0        | 5.3            | 5.26±0.25     | 2.3           | 2.42±0.16      | 1.94±0.15      | 2.56±0.14      | 1.70±0.13      |
| 12.0       | 9.0            | 8.98±0.55     | 4.4           | 5.04±0.41      | 4.23±0.35      | 4.73±0.33      | 4.09±0.40      |
| 16.0       | 12.7           | 12.67±0.91    | 7.0           | 7.89±0.42      | 6.64±0.61      | 7.06±0.59      | 7.40±0.90      |

in TOF spectrum. For example, the pulse height spectrum for $E_n$=12.7 MeV (at $E_p$=16 MeV) has been obtained with a prompt gate (65-70 ns) in TOF spectrum and the background pulse height spectrum has been obtained for the time window 85-90 ns in TOF spectrum. The background subtracted pulse height spectra are shown in figure 11 for various neutron energies.

There are several factors which contribute to the shape of the pulse height response such as nonlinear light output with energy, finite detector resolution, multiple scattering from hydrogens and carbons and detector size [1]. It can be mentioned that the pulse height response of the liquid scintillation detector to the neutrons is nonlinear and normally measured using monoenergetic neutrons produced via (p,n) and (d,n) reactions. The empirical relations guided by experimental observations [13, 14] are used to compare pulse height response of LS detector.

The electron energy equivalent light output obtained from the measurements with plastic and liquid scintillators of different size, shape and energy thresholds [13]. The parametric form of light output over a wide energy range from 1 MeV to 300 MeV is given by

$$E_{ee} = a_1 T_p - a_2 [1.0 - \exp(-a_3 T_p^{a_4})]$$  \hspace{1cm} (4.1)

where, $a_1$=0.83, $a_2$=2.82, $a_3$=0.25, $a_4$=0.93 and $T_p$ is the energy of the recoil nucleus.

The pulse height in terms of electron energy equivalent is estimated using the relations given in eq. (4.1) and eq. (4.2) for 5.3 MeV, 9 MeV and 12.7 MeV neutrons. These estimated values agree with the end point energies ($E_{\text{end}}$) of the measured pulse height spectra. A comparison between $E_{\text{end}}$ and $E_{ee}$ is given in table 1. The tabulated end point energies are also compared with the values estimated from exponential [15] and polynomial [16] forms of the LS response and show good agreement. The pulse height response is simulated using a Monte Carlo simulation.

5 Geant4 simulation for the pulse height response of the LS

A Monte Carlo simulation has been performed using Geant4 simulation tool-kit [17, 18], version Geant4.10.1 patch03, to study the response of liquid scintillator. The geometry and dimension of
the LS detector are used in the simulation as described in section 2. The active volume of the detector is taken as 55% of hydrogen and 45% of carbon. The simulation has been carried out with $10^9$ events for monoenergetic electrons and neutrons. The electromagnetic processes (photoelectric, Compton scattering, pair production and annihilation, electron Bremsstrahlung, electron scattering and electron ionization) have been used to simulate the electron response of the detector. The neutron cross section data and QGSP_BIC_HP (QGSP is for Quark Gluon String and Precompound model, BIC is for Binary Cascade and HP is for high precision physics model for energy < 20 MeV) physics list have been used for the simulation of fast neutron response. The simulated data of LS detector has been convoluted with the energy dependent resolution function as described in figure 6. The events in which energy of electron deposited in the LS when the Compton back-scattered gamma ray is detected in the BaF$_2$ detector are selected for the comparison with the measurement. Figure 12 shows the comparison of simulated and experimental data for $^{60}$Co source. It is observed that the simulated spectrum matches well with the measured data in the peak region. The background due to surrounding materials is not considered in this simulation which leads to a discrepancy observed at lower part of the simulated spectrum. The Geant4 simulation has also been performed for monoenergetic neutrons taking into account the non-linear response of the LS. The simulated response at $E_n=5.3$, 9 and 12.7 MeV are shown in figure 13. It is found that the simulated results compares with the measured neutron response of LS. The observed mismatch between the measured and simulated response may be due to non-consideration of various factors in the simulation such as BaF$_2$ array used for gamma rays detection or the surrounding materials of in the experimental hall.

6 Summary

In summary, we report a measurement and simulation of the response of a liquid scintillation detector (EJ-301) to monoenergetic electrons and neutrons. The characterization of LS has been carried out for the PSD, TOF and pulse height response using monoenergetic electrons by measuring Compton tagged electrons and monoenergetic neutrons produced via the $^7$Li(p,n$_1$)$^7$Be$^*$ (0.429 MeV) reactions. The observed electron response is found to be linear up to $\sim$4 MeV in the present experiment and
Figure 13. Pulse height responses of the liquid scintillator at $E_n=5.3$, 9, 12.7 MeV and solid lines are the Monte Carlo simulation of the energy response using Geant4.

resolution of the detector at 1 MeVee is about 11.0%. The figure of merit for the neutron and $\gamma$-ray discrimination is 1.8 at 1 MeVee. The measured response of the liquid scintillator to electrons and neutrons agrees well with the results obtained from Geant4 simulation.

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