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The measurement of liquid scintillator nonlinear response and intrinsic energy resolution

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Abstract. For Jiangmen Underground Neutrino Observatory the requirements $< 1\,\%$ energy scale uncertainty and 3 % at 1 MeV energy resolution are crucial in order to determine neutrino mass hierarchy. In this study, we focus on non-linearity due to ionization quenching and intrinsic energy resolution of the liquid scintillator. To measure them a small-scale laboratory setup was developed and the measurement of Birk's quenching constant $kB = 0.0196 \pm 0.0019$ (stat) $\pm$ 0.0030 (syst) cm/MeV was provided. With the assumption of negligible light collection term, intrinsic energy resolution term was determined: $v_{int}(50\text{ keV}) \approx 0.02 \pm 0.005$. This value is comparable with the statistical term of JUNO, therefore the effect could significantly contribute into the total energy resolution at this energy. Further studies should be directed toward accurate estimation of light collection effects.

1. Introduction

JUNO (Jiangmen Underground Neutrino Observatory) is a multipurpose reactor experiment to study antineutrino oscillations with a baseline of about 53 km [1]. The main goals of the experiment are to determine the neutrino Mass Hierarchy (MH), accurate measurement of the oscillation parameters and the study of reactor neutrino fluxes. In addition, it is also possible to detect solar, atmospheric and geoneutrino, neutrinos from the supernova and search for exotic particles and processes.

The linearity of the energy scale and the energy resolution are highly relevant to the performance of the detector and in particular to the MH determination. JUNO has very strict requirements: $< 1\%$ uncertainty of the energy scale and 3% at 1 MeV for the energy resolution. These parameters could be determined by analytical procedure and detector calibrations combined with Monte Carlo simulations [2]. The goal of the present work is to develop a reliable experimental technique to measure the nonlinear response of the liquid scintillator to low energy electrons ($T_{kin} < 100$ keV) and intrinsic energy resolution, providing a complementary determination of parameters which characterize the detector response.

The amount of light produced by incident particle $L(T_{kin}, kB)$ as a function of its initial energy is well described by the empirical expression which incorporates non-linear response due to ionization quenching [3]:

$$L(T_{kin}, kB) = Y_p \int_0^{T_{kin}} \frac{dE}{1 + kB \cdot dE/dx},$$

where Y_p is the light yield in [photons/MeV], dE/dx is the energy losses of the particle and kB in [cm/MeV] is characterizing Birks' quenching constant.

The energy resolution is represented by the relative variance of the collected charge Q:

$$\left(\frac{\sigma_E}{E}\right)^2 \approx \left(\frac{\sigma_Q}{Q}\right)^2 = v_Q = v_p + v_d + v_{st} + v_{int},$$

where the term v_p is related to the light collection variation. Monte Carlo simulations of the detector may provide a useful information about this term. In principle, if the position of an event in a detector is precisely known this term could be determined. v_d is the PMT's dark counts variation term. It rapidly falls down with an increase of energy and presented only in large-scale experiments. $v_{st} = \frac{1+v_m}{N_{pe}}$ is the square of the statistical term. The additional term v_m in the numerator represents fluctuations of the gain. The term

$$v_{int} = v(N_{phot}) - \frac{1}{N_{phot}},$$

called intrinsic energy resolution (IER), is associated with a variation of light emitted by liquid scintillator. The intrinsic resolution is a measure of the deviation of the statistics of the photon emission from the Poisson distribution.

2. Experimental technique

For both energy non-linearity and energy resolution measurements, the Compton coincidence technique with High Purity Germanium (HPGe) detector gives promising results. Several studies were dedicated to liquid scintillator non-linearity measurements [4, 5, 6]. In [7] the only attempt to measure intrinsic energy resolution of a liquid scintillator was reported.

The sketch of the experimental setup is shown in figure 1. The setup consisted of a quartz cell filled with a liquid scintillator (LAB + 1.5 g/l PPO) and coupled with a photomultiplier (PMT), HPGe detector and monoenergetic ^{137}Cs gamma source.

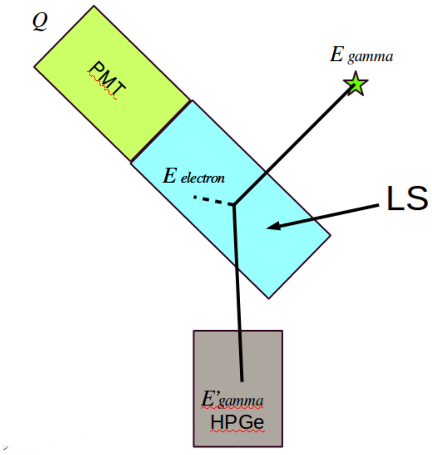

Figure 1. Sketch of the experimental setup for liquid scintillator response study.

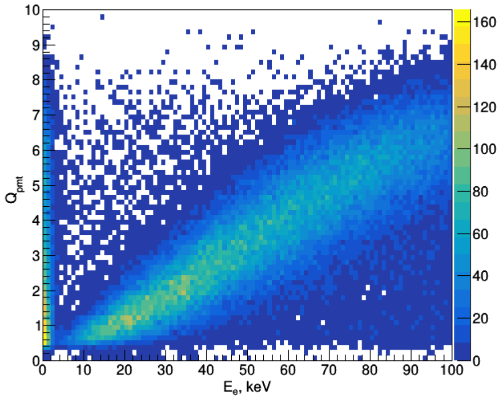

Figure 2. Coincidence histogram for Compton electrons produced in the liquid scintillator. On the X-axis the energy of the Compton electrons reconstructed as $E_e = E_\gamma - E'_\gamma$. Y-axis is the corresponding charge Q collected by the photomultiplier (arbitrary units).

The superb energy resolution of the HPGe detector provides a possibility to reconstruct the energy of Compton electron directly from the difference between initial energy E_γ and energy deposed in HPGe detector $E_\gamma^{'}$:

$$E_e = E_\gamma - E_\gamma^{'}$$

With this method, the energy of scattered electron could be reconstructed regardless of the scattering angle. Acquiring the coincidence events in HPGe detector and the liquid scintillator one can measure energy response of the liquid scintillator to low energy electrons. The corresponding coincidence histogram is shown in figure2. The diagonal structure contains information about non-linearity and energy resolution of the liquid scintillator. By slicing the histogram along the x-axis, one-dimensional histograms of the liquid scintillator response for a given electron energy E_e were obtained. These histograms contained information about the mean Q and the standard deviation σ_Q of the response which were extracted by the fitting procedure. To incorporate the measurements of the stability and reduce related systematic effects, the scales of PMT and HPGe were calibrated and a variation of the signal was corrected. The system was equipped with a picosecond laser to calibrate PMT in terms of the number of photoelectrons for precise determination of v_{st} term.

The configuration of the setup was chosen to keep gamma scattering angle small $\theta = 0 - 20°$. At such small angles, the effects of non-uniformity of the light collection are supposed to be negligible since all scattering events are happening in the central kinematically allowed region.

3. Monte Carlo simulation

To study the systematic effect related with multiple Compton events a GEANT4-based Monte Carlo program was developed. Biased events were distinguished at some level of acceptance ϵ_E by the condition:

$$|E_{MC}^{vis} - L(E_\gamma - E_\gamma^{'}, kB)| \leq \epsilon_E$$

where $E_{MC}^{vis} = \sum_i E_{Compton}^{vis} = \sum_i L(E_{Compton}, kB)$ is the visible energy in the liquid scintillator and $L(E_\gamma - E_\gamma^{'}, kB)$ is the expected visible energy if only one Compton scattering event occurred. The condition was applied before smearing by the energy resolution. The value ϵ_E was arbitrary set at 0.15 keV (0.3 % systematic deviation at 50 keV). The condition split all events (figure 3, black histogram) into two groups: events which have a bias less than 0.15 keV (green) or more than this value (red). Only 4 % of events didn't pass the condition, deviating more than ϵ_E from the non-biased position. Thus, the overall shift due to multiple Compton events is much less than the chosen level of acceptance << 0.15 keV and, practically, it is not significant for given experimental configuration and energy range.

4. Results and conclusions

Data analysis of the coincidence histogram and the fit with $L(T_{kin}, kB)$ function provided a measurement of the ionization quenching constant:

$$kB = 0.0196 \pm 0.0019\ (\text{stat}) \pm 0.0030\ (\text{syst})\ \text{cm/MeV}$$

Thanks to the calibration of the PMT, the statistical term v_{st} (figure 4, small dots) was precisely determined and the contribution of the intrinsic energy resolution v_{int} (figure 4, large points) was extracted from the total relative variance v_Q as $v_{int} = v_Q - v_{st}$.

The magnitude of IER was smaller compared with the value found in [7] for EJ301 liquid scintillator (figure 4, triangles). However, since both effects should depend on the type and composition of the liquid scintillator the comparison with the present data is only indicative.

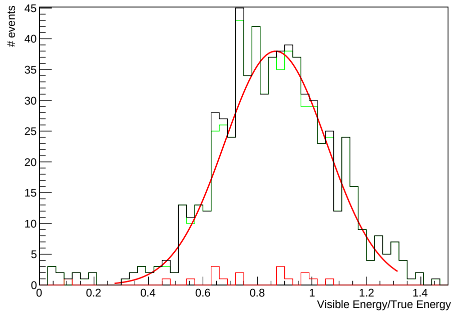

Figure 3. Example of a Monte Carlo simulated one-dimensional histogram of the setup response for $E_e = 48.5 - 51.5$ keV. Events with negligible multiple Compton contribution are denoted by green. The red histogram is a distribution of the significantly shifted events $(\Delta E^{vis}_{bias} > \epsilon_E)$.

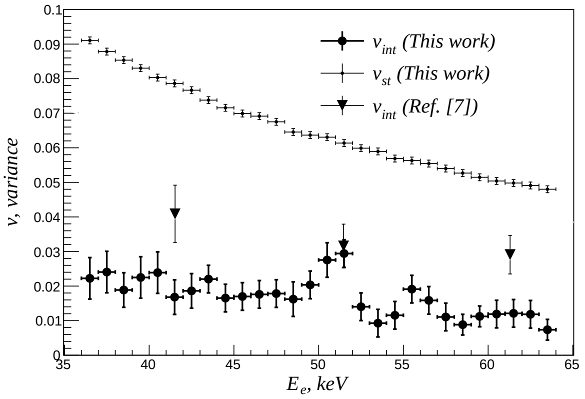

Figure 4. The measurement of v_{st}(small points) and v_{int} (large points) terms in the energy range 36-63 keV. The result for v_{int} from [7] is provided for comparison (triangles).

The comparison of the found IER with the expected energy resolution of JUNO at $E_e = 50$keV shows that $v_{int}(50\,\text{keV})$ is similar to $v_{st}^{JUNO}(50\text{keV}) \approx (0.03)^2/E_e) = 0.018$. Therefore, IER may play an important role in the future large scale detectors, deteriorating overall energy resolution.

The result was obtained assuming that the effects of the light collection could be neglected $(v_p/v_Q << 1)$. As an outlook, the precise estimation of the light collection for this setup configuration should be conducted in order to ensure that the contribution of v_p is not significant to mimic the observed intrinsic resolution effect.

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