Measurement of Liquid Scintillator Nonlinearity

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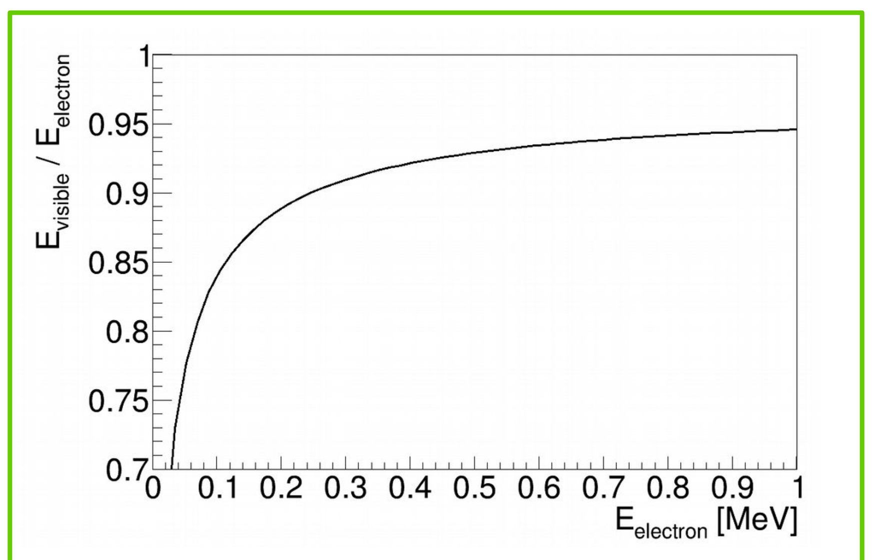
Organic Liquid Scintillators

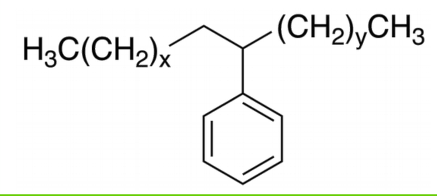
- Hydrocarbon compounds containing benzene-ring structures.
- Ionizing particles excite scintillator molecules which then emit light that can be detected by a PMT.
- The dependence of the amount of scintillation light L on the energy E deposited by the incident particle is not exactly linear.
  - The deviation is due to quenching interactions between the excited molecules along the path of incident particle, i.e., interactions which drain energy which would otherwise go into luminescence. Since a higher ionizing power produces a higher density of excited molecules, more quenching interactions will take place for these particles [1].
  - Nonlinearity can be described by semi-empirical Birk's formula [1]: $$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}}$$



Example of a nonlinearity curve for electron

Reactor Neutrino Experiments

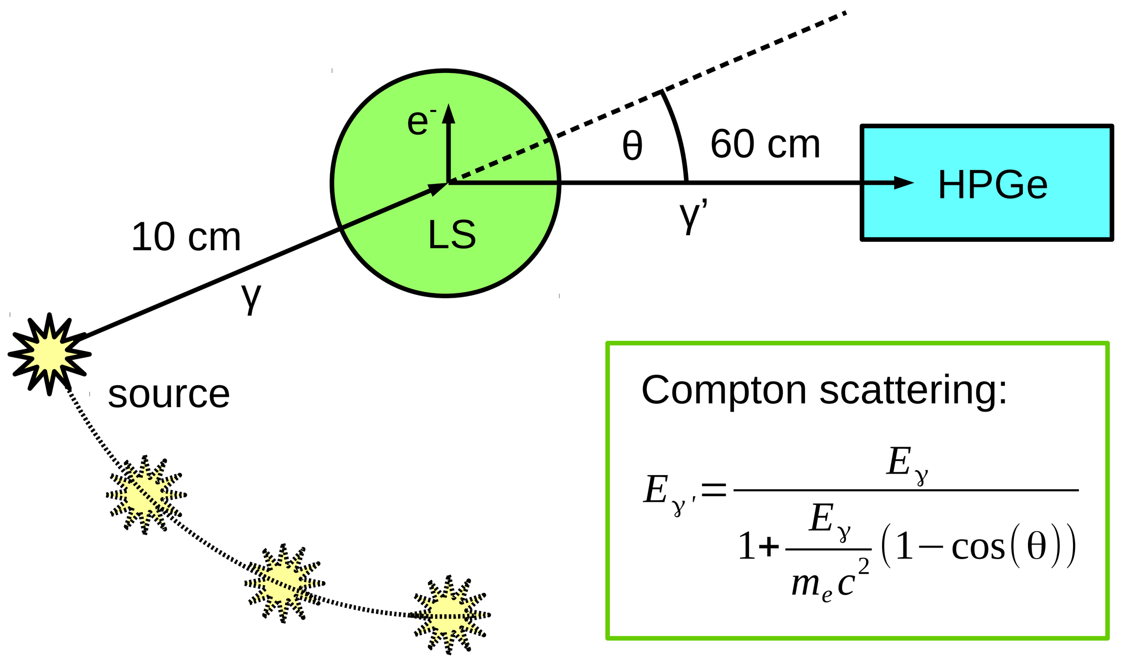
- Many experiments that measure oscillations of reactor neutrinos use liquid scintillators for their central detectors (e. g. Daya Bay [2], Double Chooz [3], Kamland [4], Reno [5], in future JUNO [6]).
- Precise measurement of neutrino energy is crucial, especially for JUNO experiment.
- Neutrinos typically interact via inverse beta decay: $$\bar{\nu}_e + p \rightarrow e^+ + n$$
- Neutrino energy can be deduced from the positron energy; however, measurement of the positron energy is affected by quenching.



Linear alkylbenzene (with various solutes) is widely used in reactor neutrino experiments.

Experimental Principle and Setup

- Mono-energetic gamma of well-known energy interacts via Compton scattering in the liquid scintillator (LS) transferring part of its energy to an electron.
- Recoiled electron causes production of scintillation light which is detected by a PMT. It is affected by quenching.
- Energy of the scattered gamma is precisely measured by a HPGe detector. Thus the energy deposited in the LS can be determined.
- Signal from the LS is compared to the energy determined by the HPGe detector.
- Energy transferred in Compton scattering depends on the scattering angle. Thus, various energies can be scanned by moving the source around the LS.



Compton scattering:
$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos(\theta))}$$

- ^{137}Cs (662 keV), ^{22}Na (511 keV annih. & 1275 keV) ^{60}Co (1173 keV & 1332 keV), ^{24}Na (1369 keV & 2754 keV) used (separately) for nonlinearity measurement.
- ^{241}Am (59.5 keV) for LS & PMT stability monitoring.
- Linear alkylbenzene based LS is inside cylindrical vessel with bottom attached to a 3'' PMT and sides made of reflective surface (PTFE).
- The LS and sources are placed on a rotating table.
- The HPGe detector is fixed.
- Data from the LS and HPGe are taken in coincidence.

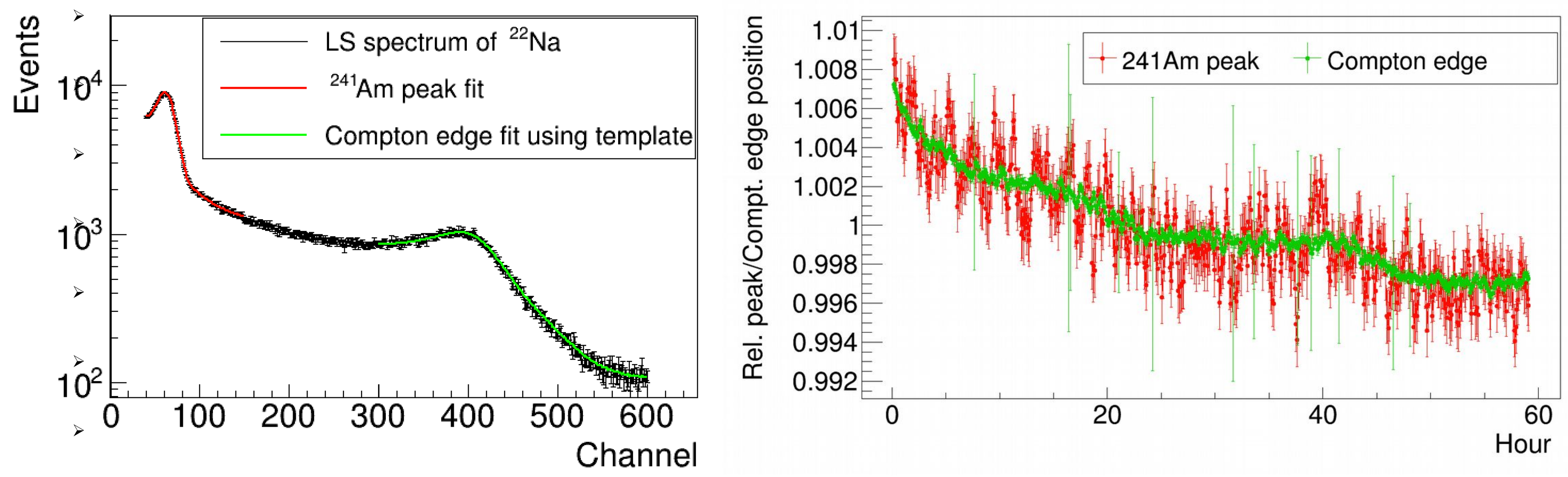
Energy Scale Stability & Readout Nonlinearity

HPGe Calibration & Stability

- Gamma lines of 8 radioisotopes used for calibration (^{22}Na, ^{60}Co, ^{133}Ba, ^{137}Cs, ^{152}Eu, ^{208}Tl, ^{226}Ra, ^{241}Am), difference between reconstructed and table values within 0.04 keV.
- Energy scale is stable within 0.1%.

LS & PMT Readout Stability

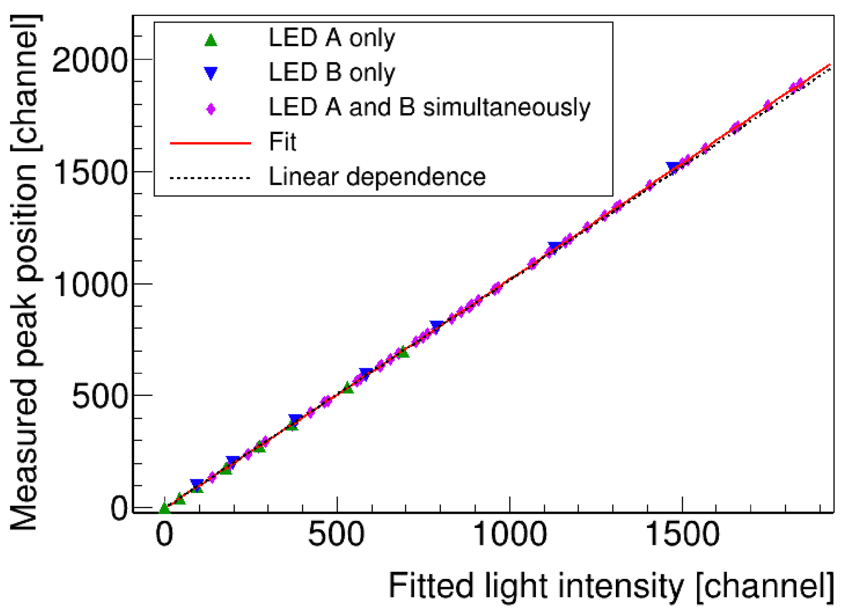
- Energy scale instability is in order of % → position of ^{241}Am peak and position of main Compton edge were used to make corrections with 5 minutes step:



^{241}Am peak and Compton edge in ^{22}Na spectrum and relative stability correction

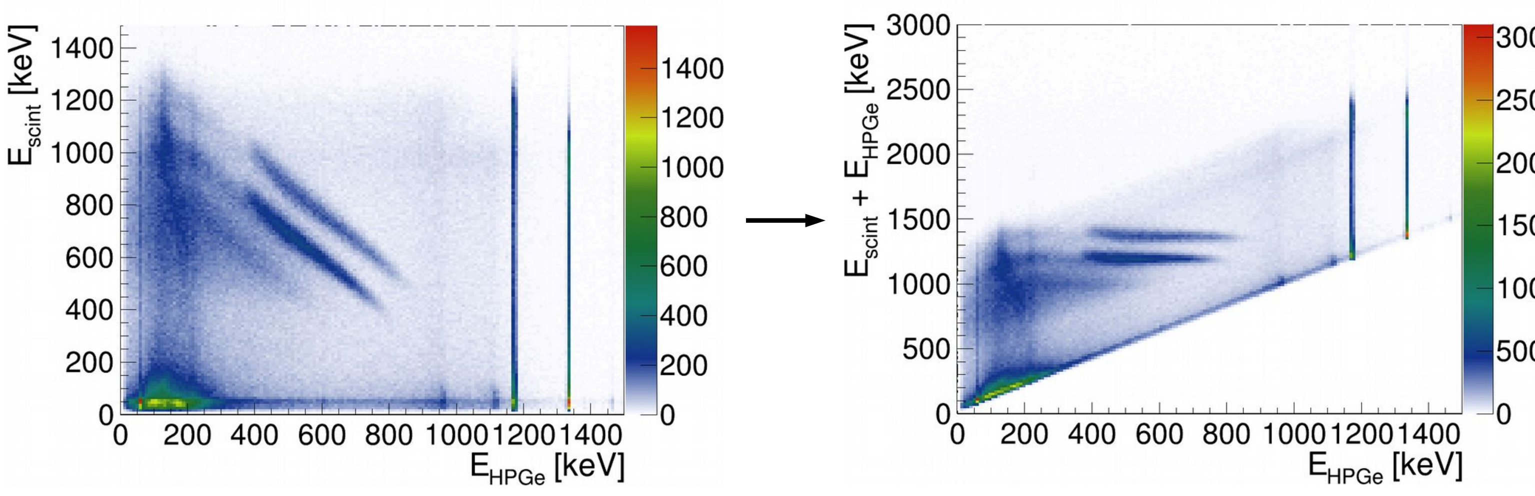
PMT Readout Nonlinearity

- PMT was illuminated by LED A, LED B and both of them triggered by the same pulse generator. Signal of LEDs flashing simultaneously was compared to sum of signals of LEDs flashing individually.
- Simple relation between observed signal S and light intensity L was assumed: $$S = L - \beta L^2$$
- Parameter β can be obtained from fit.
- Deviation from linearity < 1% @ 2 MeV, corresponding correction was made.

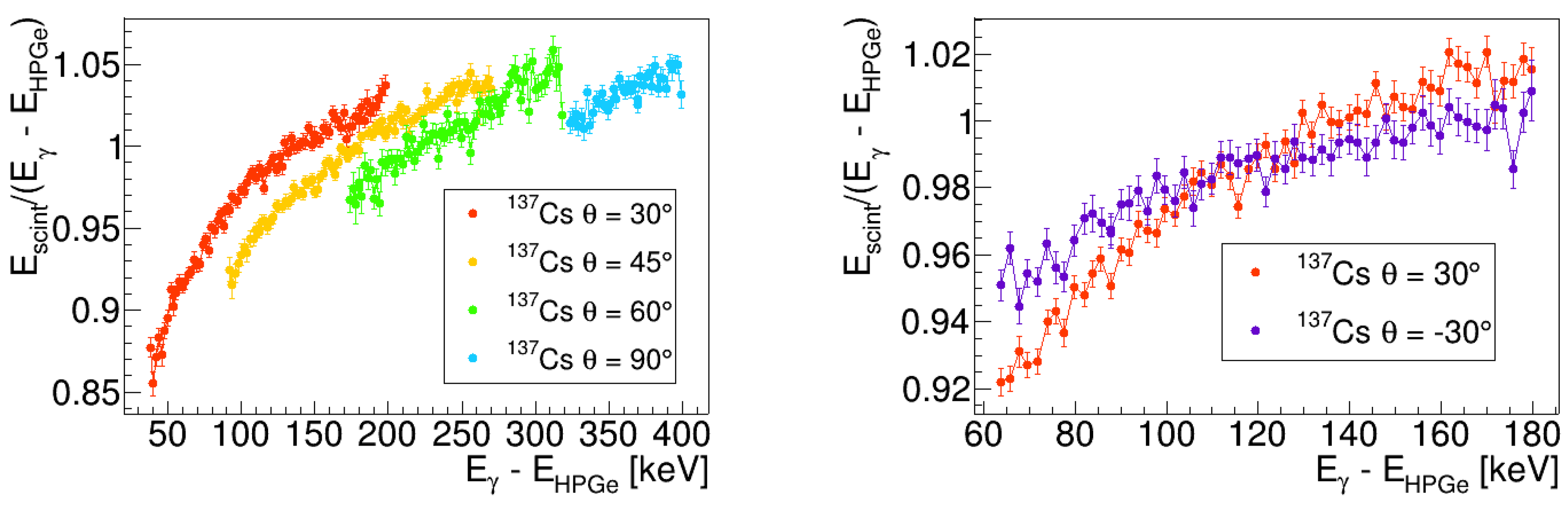


LS Nonlinearity Data Analysis

- The LS is linearly 'pre-calibrated' at certain energy using data from the HPGe.
- Events are transformed from E_{scint} vs E_{HPGe} to $E_{scint} + E_{HPGe}$ vs E_{HPGe}:



- Projection to $E_{scint} + E_{HPGe}$ axis is made for various bins in E_{HPGe} and the peaks are fitted. E_{scint} is extracted from the fitted value and compared to $E_\gamma - E_{HPGe}$.
- LS nonlinearity was observed in several samples. Ideally, data points obtained with the apparatus set to various angles should partially overlap creating nonlinearity curve, especially for measurements done at 30° and -30° (i.e. 30° angle set in opposite direction).



- However, there are detector-induced effects present that make precise deduction of k_B difficult; e.g. PMT offset, light collection and PMT efficiency nonuniformities.

References

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