Measurements of the Cherenkov light yield in liquid scintillators at the JINR test stand

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Abstract

Various scientific experiments use liquid scintillators like the core sensitive element of their detectors. It is crucial to have a good knowledge of the basic properties of scintillators for precise reconstruction of the primary particle energy. Cherenkov light component to the liquid scintillators total light yield is one of these properties.
The special test stand was constructed at JINR to measure the Cherenkov light contribution to the mineral oil based and LAB liquid scintillators total response. The main idea was to measure the light output below and above the Cherenkov light emission threshold and extract its fraction.

Introduction

Scintillators

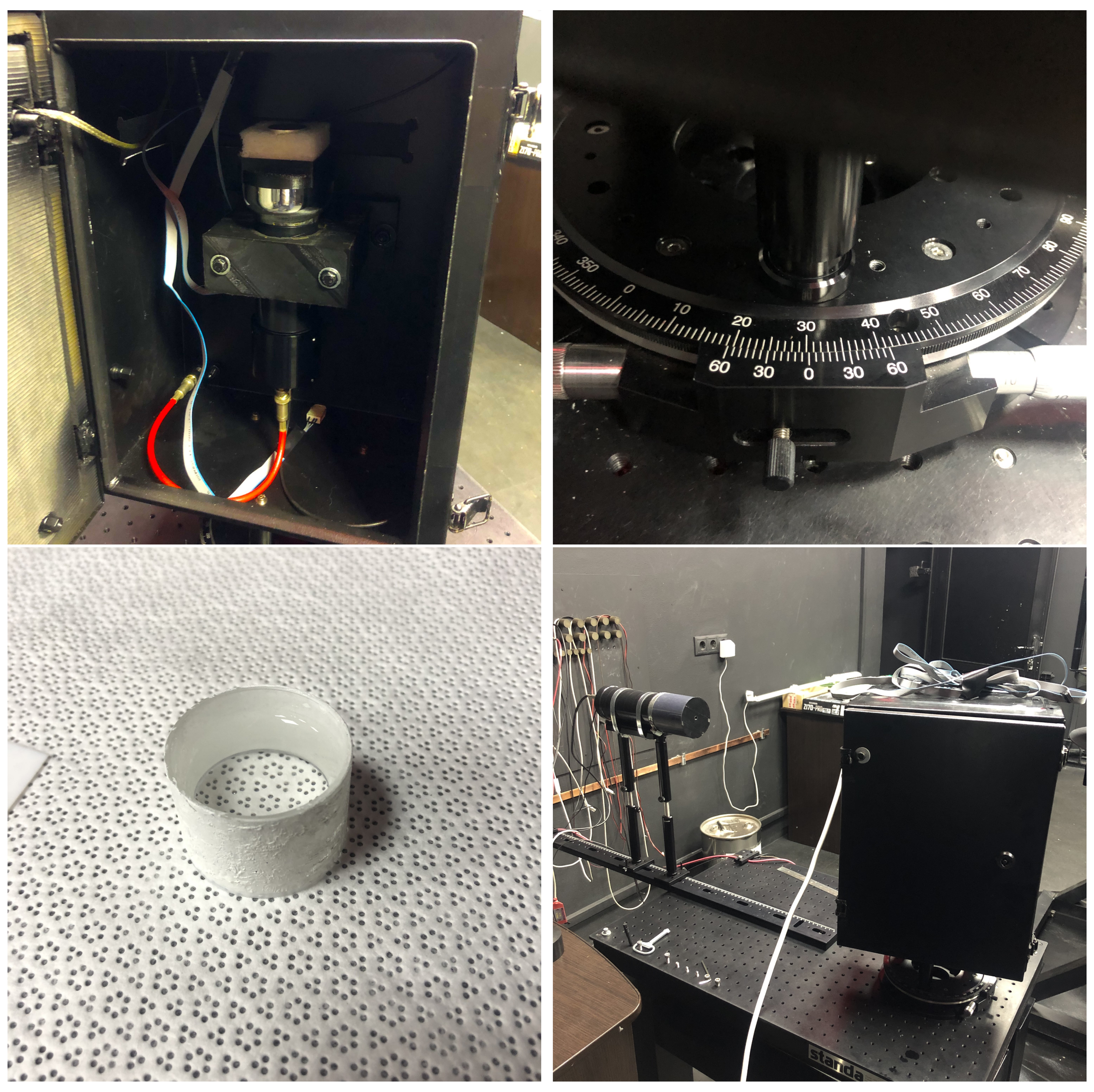
One of the methods of detecting ionizing radiation in experimental physics is to use scintillators. A charged particle passing through a substance deposits its energy within. Part of this energy converts into photon production. Some substances, called scintillators, have a significant conversion so that the generated light can be detected and measured by means of photosensors or photodetectors. The spectrum and intensity of the light signal depend on the intensity of the energy release, the type of passing particle, and properties of the scintillator. These are the main properties of a scintillator: light output (including Cherenkov), the spectral composition of radiation, energy resolution, decay time, radiation resistance, radiation length, and quenching factors (Birks's effect).

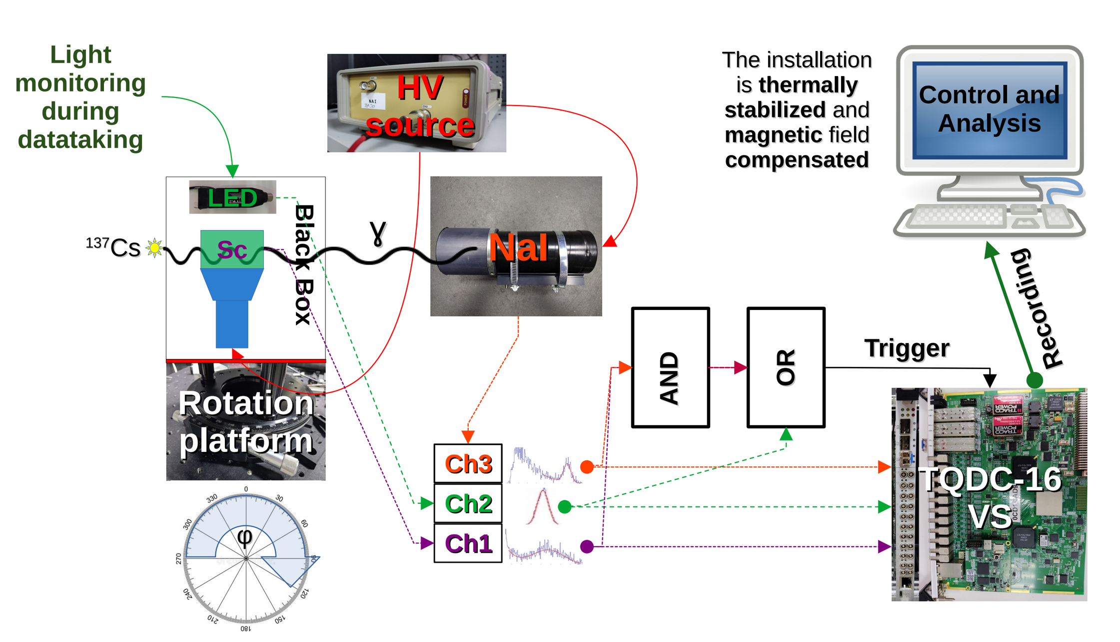
Cherenkov light

When a high-speed electron (or other charged particle) passes through a dielectric medium, the electromagnetic field will be disturbed and electrically polarized. A coherent shock wave is left in the medium in the wake of the particle. If the velocity of the charged particle is less than that of the speed of light in the medium, then the polarization field which forms around the moving particle is usually symmetric. The radiated waves bunch up slightly in the direction of motion, but they do not cross. However, if the particle moves faster than the speed of light inside the medium, the emitted waves add up constructively leading to coherent radiation at angle θ with respect to the particle direction, known as Cherenkov radiation. The signature of the effect is a cone of emission in the direction of particle motion.

Hardware setup

The stand consists of a few components:
The **Black Box** is the light-tight metal box with equipment with connectors feedtrough. It is used to isolate the inner structure of the box from outer light and electromagnetic noise. The Black Box is attached to a **rotation platform**.
The PMT (**P**hoto**m**ultiplier **t**ube, *3" Hamamatsu R12772*) with divider and **cylindrical cuvette** made of optical glass (it's ⌀ is 1 inch) are located inside the Black Box in a vertical position. The cuvette with a liquid scintillator inside is used like the first detector.
2" **NaI** with *2'* PMT is used like the second detector.
All supporting electronics as ADC (**A**nalog-to-**d**igital **c**onverter) DRS4 with 5 GHz sampling and 14-bit amplitude resolution, High-Voltage sources and PC with the required software, also mineral oil-based (one that is used in the NOvA experiment Far Detector) and LAB-based with 1 g/l PPO scintillators [great thanks to the **NOvA collaboration** and **Nemchenok I.B.** for the provided samples] along with different γ radioactive sources are used like the final part of our setup.





Methodical aspect

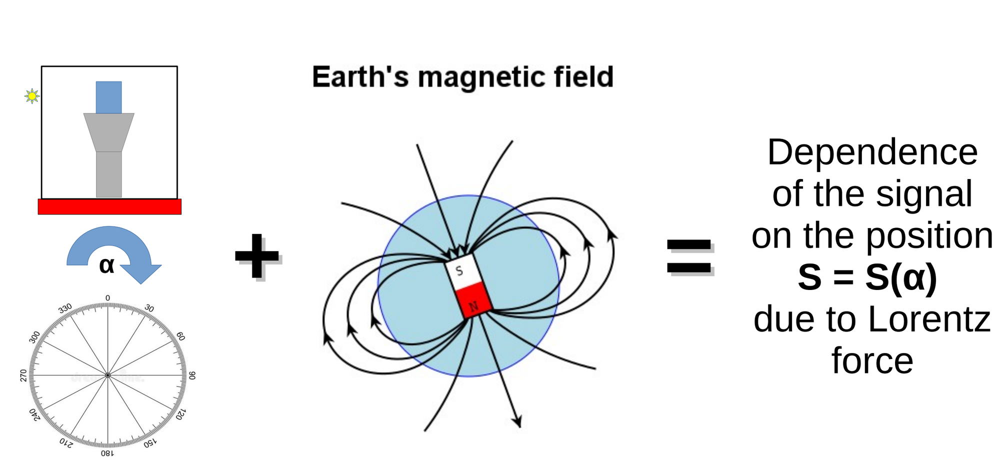
The general idea of the measurement is to use Compton γ-scattering to "prepare" electrons of various energies, and hence different speeds, in a liquid scintillator.

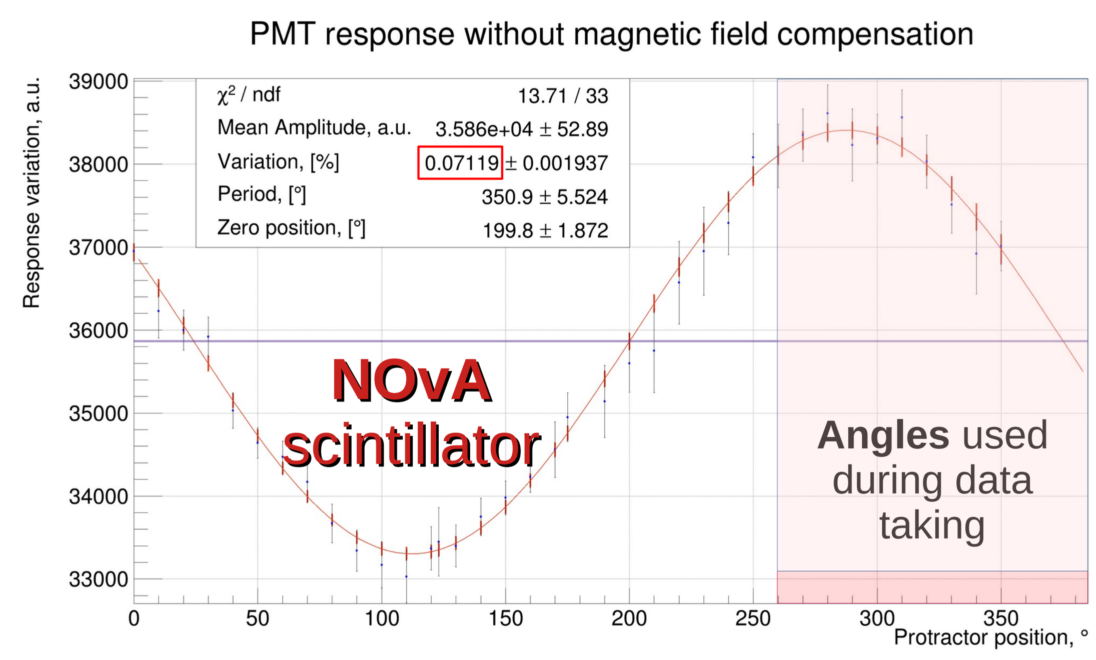
$$E_e = \frac{E_\gamma}{1 + \dfrac{m_e c^2}{2E_\gamma \sin^2 \dfrac{\theta}{2}}} \tag{1}$$

- Use monochromatic source ^{137}Cs with $E_\gamma = 661.7$ keV.
- Rotate the Black Box with cuvette inside that makes the scattering angle adjustment.
- Make an analysis of NaI spectrum for each angle.
- Select events in photopeak (full energy dissipation) region in the NaI spectrum and produce liquid scintillator response. This method allow excluding additional Compton scatters of γ-quanta outside the Cuvette while travelling to the second (NaI) detector.
- Convert the Angle into the Energy using Eq. 1.
- Apply Birks's correction to the light output.
- Fitting below and above the Cherenkov threshold and extract the **slope difference**.

Possible sources of signal discrepancy

It is critical to have linear photosensor response during all datataking time.
Temperature influence: Both photosensors were tested using ^{137}Cs and LED. Temperature variation was from $+18°$ to $+26°$. Signal fluctuation was about 1-2% for there whole temperature range. It was decided to fix the temperature at 22 $°C$ using air conditioner system.
Magnetic field influence: During the datataking we rotated the Black Box with liquid scintillator from 260° to 360° on protractor scale. As our PMT is [*3" Hamamatsu R12772*] rather small but still can "feel" the influence of Earth magnetic field our signal depends on the position [$S = S(\alpha)$] of the Black Box.

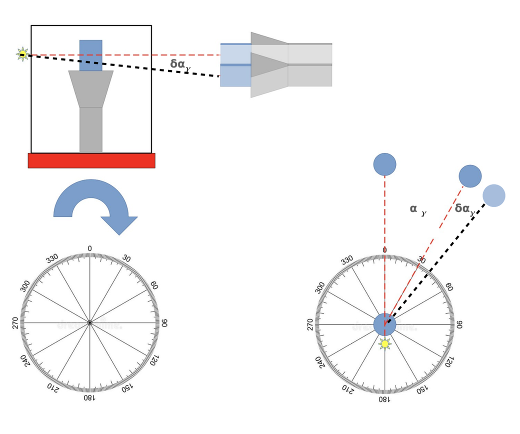


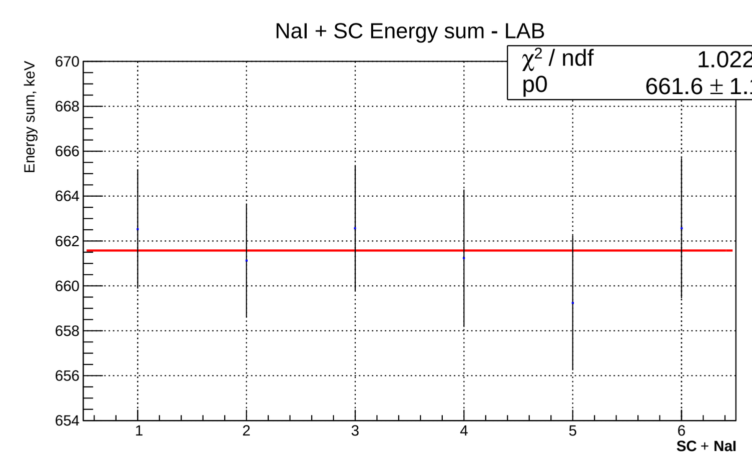


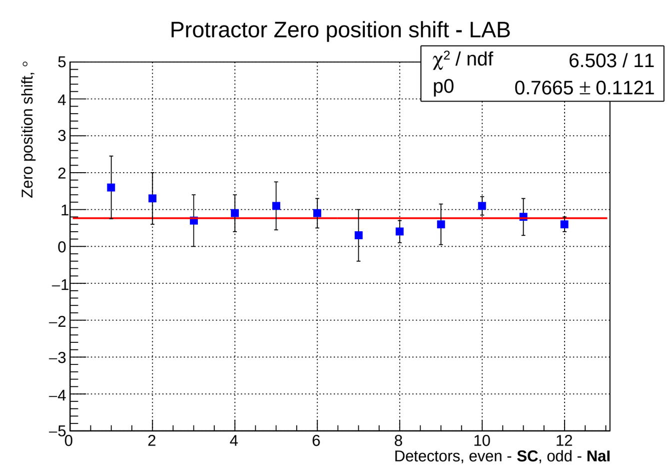
To minimize this signal discrepancy source we compensated the Earth magnetic field using **Helmholtz coils**. The whole protractor circle [360°] was again tested using ^{137}Cs gamma source and LED for better precision and equivalence check between two initial pulses. PMT response variation was decreased from $\pm[7-9]$% to $\pm[1-1.5]$%. Remaining signal variation values were taken into account during the analysis procedure for both liquid scintillators.
PMT response non-linearity influence: During the calibration procedure (we used ^{133}Ba, ^{22}Na, ^{228}Th, ^{137}Cs γ sources) for scintillator we suspected the **non-linearity** of PMT response starting from $V_{PMT} = 1200V$. We replaced γ sources by LED with well **linear** light pulse output for precise measurement of PMT **non-linearity** effect. PMT response to LED light pulse was fitted by function $F = p_0 \times (1 - e^{\frac{-x}{p_1}})$. The resulting correction coefficients [up to **+4%** for $V_{PMT} = 1200V$ and up to **+13%** for $V_{PMT} = 1600V$] were taken into account during the analysis procedure for both liquid scintillators.

Angular correction studying

It is quite difficult to measure the alignment of all the setup elements better than 1°. The angular shift can be both vertical and horizontal therefore it is necessary to measure the total average scattering angle directly and compare it with the one that we set on the installation. Real **Zero** protractor position measurement was done with signal discrepancy corrections application.
Several parameters were checked during this measurement: energy output in the first and second detectors and their sum. Both detectors were calibrated using γ sources. Depending on the angle, the energy of gamma quanta from the source ^{137}Cs must be distributed between the two detectors in a certain proportion following the energy conservation law. Six angular points [50°, 60°, 70°, 80°, 90°, 100°] were checked: the sum of the energies at each point within the error limits corresponds to the primary energy of the gamma quantum from cesium, and the energy distribution between the two detectors shows an angular shift around +0.8°.

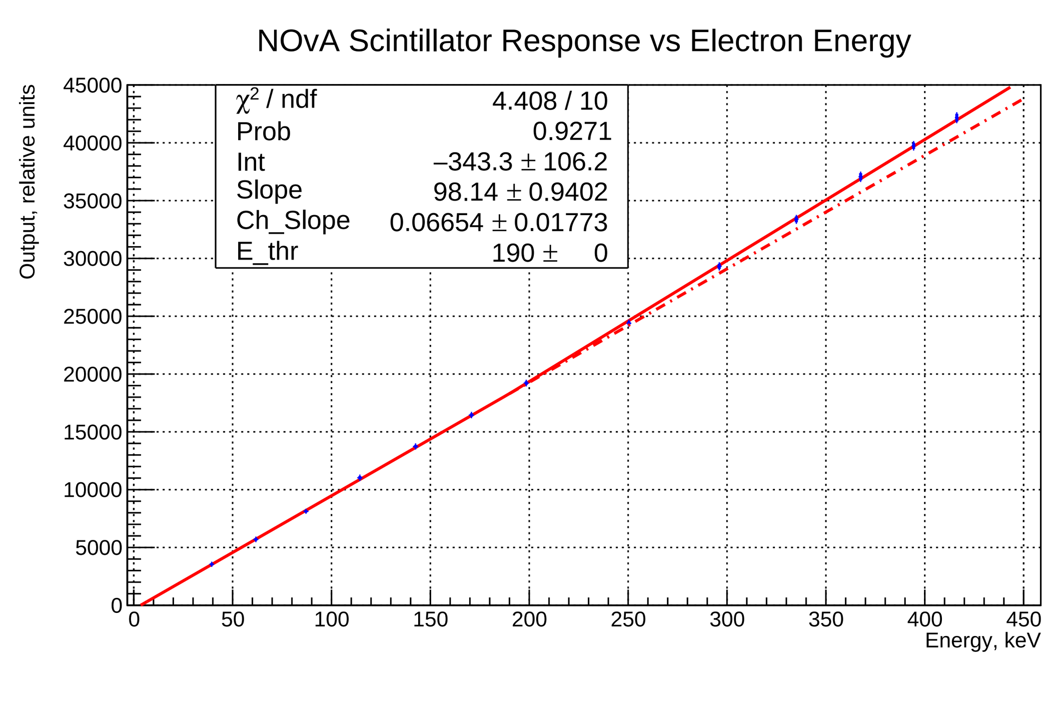


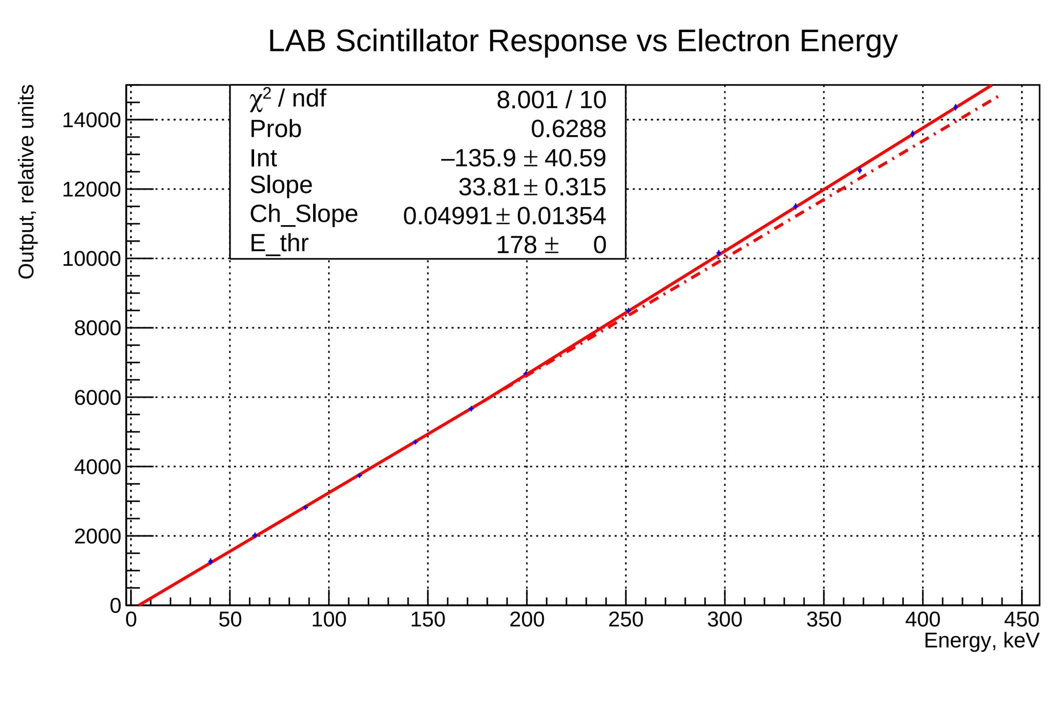




Results

Implementation of all signal discrepancy and angular corrections to the analysis along with evaluation of their impact on the final output gives **6.7±1.8%** slope change for the mineral oil-based NOvA scintillator and **5.0±1.4%** slope change for the LAB scintillator.





LAB scintillator Cherenkov light contribution value is in a good agreement with: **T. Kögler et al. Light yield and $n-\gamma$ pulse-shape discrimination of liquid scintillators based on linear alkyl benzene** and **P. Kampmann et al. A semi-analytical energy response model for low-energy events in JUNO**.