Scintillation light production, propagation and detection in the Stereo reactor antineutrino experiment

Christian Buck, Manfred Lindner and Christian Roca
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
E-mail: buck@mpi-hd.mpg.de, lindner@mpi-hd.mpg.de, roca@mpi-hd.mpg.de

Abstract.
The Stereo experiment’s detector has been optimized to observe reactor antineutrinos via inverse beta decay within a 1800 liter volume filled with Gadolinium-doped organic liquid scintillator (LS). The main requirements for the scintillator in Stereo are compatibility with detector materials as the acrylic vessels, transparency, light yield, pulse shape discrimination capabilities as well as chemical and optical stability over several years of data taking. With these conditions in mind, the composition of the LS is mainly a mix of 75% LAB, 20%PXE and 5% DIN combined with the two wavelength-shifters PPO and Bis-MSB. The final admixture after the full scale production lead to an attenuation length of more than 5 meters for optical photons of 430 nm.

The scintillation light produced in the Gd-loaded target volume and the Gd-free outer crown is detected by 48 eight inch PMTs on top of the detector. A correct performance of the PMTs has been ensured through several tests. Common characteristics for PMTs as gain, single photoelectron peak, time behaviour, dark rate and afterpulse ratio were measured resulting in a complete agreement with the manufacturer values.

1. Introduction
In 2011, the electron antineutrino flux from fission processes was reevaluated. Together with the decreased life-time measurement of the neutron, the total $\bar{\nu}_e$ flux from nuclear reactors was theoretically increased roughly by 6%. This study led to a reanalysis of previous reactor neutrino experiments [1] which resulted in a deficit of about 2.7$\sigma$ significance relative to the expected flux. This reactor neutrino anomaly (RAA) could be explained by a short baseline $\bar{\nu}_e$ oscillation towards a fourth, light and sterile neutrino state. The best fit parameters for this new oscillation able to match the RAA are $\sin^2(2\theta_{\text{new}}) = 0.17 \pm 0.04$ and $\Delta m^2_{\text{new}} = 2.3 \pm 0.1$eV$^2$ at 1$\sigma$.

The Stereo experiment aims to test such an hypothesis [2] by measuring with high precision the evolution of the $\bar{\nu}_e$ energy spectrum at short distances from the source since at large distances this oscillation is smeared out. More concretely, the detector is centred about 10 m away from the compact 58 MW research reactor at the Institut Laue-Langevin (ILL) in Grenoble, France (see [3]). According to the RAA best fit parameters, the oscillation length for reactor antineutrinos with energies $\sim 4$ MeV is around $\sim 4$ m. Therefore, the detector is 2.2 m long and is segmented in six identical cells to measure the relative distortions of the $\bar{\nu}_e$ energy spectrum between them. Neutrinos emitted from the reactor will be detected via Inverse Beta Decay (IBD) on H nuclei,
Both the \( e^+ \) and the \( n \) give correlated signals, and to optimize the detection efficiency the target cells will be filled with an organic liquid scintillator (LS) doped with Gadolinium (Gd). On one hand, the \( e^+ \) or prompt event will ionize the medium right before annihilating and releasing two 0.511 MeV gammas. On the other hand, the \( n \) takes about \( \Delta t \approx 30 \mu s \) to be captured and because of that, it is called delayed signal. It can be easily tagged by the characteristic \( \gamma \) radiation from either Hydrogen or Gadolinium neutron capture. Detailed information about neutron and \( \gamma \) background reduction can be obtained in [4].

All the scintillation light generated in this coincidence signal will be collected by a set of 48 photomultiplier tubes (PMTs) on the top of the detector and processed by the dedicated electronics of Stereo (see [5]). Thanks to the reflective plates coating the inner wall of the cells, the photons are directed to the PMTs increasing the detection efficiency for every event.

2. The organic liquid scintillator

Over the course of several decades, organic liquid scintillators (LS) have formed the basis for successful reactor neutrino detectors. The main feature of LS is indeed the scintillation produced by an ionizing particle passing through the liquid. The Stereo detector is filled with 1800 liter of LS which is in turn a compound of several organic scintillators. Namely: 75% of Linear alkylbenzene (LAB), 20% of Phenylxylylethane (PXE) and 5% of Di-isopropynaphthalene (DIN). Traditionally the most common solvent for high light yield scintillators in neutrino experiments has been pseudocumene (PC). Nowadays, however, safety considerations have taken ground and the focus shifted to high flash point solvents, like LAB, PXE and DIN. The counterpart is a lower light yield in comparison to PC. The main component in Stereo, LAB, has a slightly lower light yield than other typical organic scintillator solvents. However, it compensates by being specially versatile due to its high transparency to scintillation light, material compatibility and low price. The second solvent, PXE, increases the light yield and is a high flash point solvent as well. Finally, the small amount of DIN provides the experiment with specially high PS capabilities [6] even in low concentrations. As stated before, to perform the neutron capture in the LS a small concentration of a Gd-loaded compound is added. In the particular case of Stereo it is Gd-\( \beta \)-diketonate [8] in a concentration of 0.2%. This amount ensures an efficient Gd-neutron detection without compromising with the LS light yield.

The emitted scintillation spectrum from the solvent needs to be shifted to the most sensitive wavelength region of the PMTs. For this reason, the wavelength shifters (WLS) are diluted in small concentrations in the final mix. Their absorption band overlaps with the emission band of the solvent while their emission band is at lower energies. This overlap is usually large enough to ensure an efficient energy transfer between the molecules. Although for some applications it is sufficient to have just one WLS in the scintillator mixture, a secondary WLS may be added to improve the attenuation length of the scintillator. The main dopant is typically added at concentrations of few g/l while the secondary WLS usually has concentrations less than 20 mg. In Stereo, those fluoros are 2,5-Diphenyloxazole (PPO) and 4-bis-(2-Methylstyryl)benzene (bis-MSB) with a concentration of 7 g/l and 20 mg/l respectively. Besides PPO there are several other fluoros that have a better overlap with Bis-MSB. However, PPO is specially suitable due to its low toxicity, high solubility in the organic solvent and transparency. Therefore, usual scintillation around 280 nm is shifted by PPO to values around 350 nm so that the Bis-MSB can finally rise its wavelength up to 420 nm, lying within the optimal region of the PMTs. Because of the large scale of the neutrino detectors, several absorption and re-emission processes may take place between the initial scintillation and the optical light read by the PMT. This forces the WLS to have a very high re-emission quantum yield (\( \sim 85\% \) [6]) to ensure minimal losses and keep the total light yield high.
3. Testing the photomultipliers

The Stereo experiment will be using 48 eight inch photomultipliers placed on the top of the detector. These PMTs had to be characterised prior to their installation, and for this task the test facility chosen was at the Max-Planck-Institut für Kernphysik in Heidelberg. The tests were performed inside a dark 30 m$^3$ Faraday chamber that protected the PMTs against any external electromagnetic fields during the measurements. To prevent undesirable light reflections, the inner walls have been covered with black fire-proof fabric. Finally, the PMTs have been shielded by a $\mu$-metal cylinder in order to prevent any influence of the Earth magnetic field and neighboring PMTs. As light source to perform the characterisation tests, VME controllable 12-channel LED boards were developed by the electronic workshop at MPIK. These LEDs are configured to produce light at a wavelength of 380 nm with tunable light intensity that can be programmed for each channel individually from the single photoelectron (SPE) range up to a several tens of photoelectrons (PEs). The most important features that have been checked are:

- **Dark counts**: those are events caused by thermal emission of electrons from the photocathode which are not distinguishable from events caused by regular photoelectrons. After being exposed to light, the PMTs’ photocathode remain excited for some hours. The stabilization process has been measured and all of them showed acceptable values of dark rate.

- **Gain calibration**: a high voltage (HV) scan has been performed around the nominal voltage set by the manufacturer for every PMT. The signal current arriving at the QDC was integrated within a time window of 200 ns and amplified $\times 10$. Fitting this data for every HV value one can obtain the exponential relation between voltage and response. The parameters of the fit are the optimal voltage at which each PMT would give the desired gain, $G = 3 \cdot 10^6$ for Stereo, and the exponential factor. All PMTs have the optimal voltage within the expected voltage range between 1400 and 1900 V.

- **SPE response**: The SPE spectrum of all the PMTs have been checked using the optimal voltage. In all cases the SPE peak was centered at 4.8 pC, which corresponds to the charge of the electron after the amplification process.

- **Transit time response**: The absolute transit times were measured including an additional offset of 200 ns related to the electronics and the LED. In all cases a spread of $\Delta t \sim 3.75$ ns was measured.

- **Afterpulse (AP) probability**: sometimes residual gas inside the PMT can get ionized during the photoelectron amplification process. The remaining positive ion drifts towards the photocathode generating an avalanche of electrons soon after the first signal has passed. These spurious events could lead to a false trigger if the AP probability is too high. The studies revealed that the probability for AP to happen is roughly at 2%, which ended up being a negligible effect below the minimum energy trigger set for Stereo.

All the PMTs are now installed in the detector and ready for data taking.

References

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