Study on TPB as wavelength shifter for the new ICARUS T600 light collection system in the SBN program.

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Abstract.

In the last 30 years, the incredible experimental progress made in the studies of neutrino oscillation allowed to better understand the pattern of neutrino masses and neutrinos mixing. However, further investigation are necessary, in particular concerning a series of experimental anomalies, observed in different neutrino experiments, which are uncorrelated with each other but all hinting at oscillation phenomena. The goal of the new Short Baseline Neutrino program is to perform sensitive searches for $\nu_e$ appearance and $\nu_\mu$ disappearance in the Booster Neutrino Beam in order to understand experimental anomalies in neutrino physics and to perform the most sensitive search for sterile neutrinos at the eV mass-scale. The experiment includes three Liquid Argon Time Projection Chamber detectors located along the Booster Neutrino Beam line at Fermilab. In this paper, the functioning of the Short Baseline Neutrino far detector, ICARUS-T600, is shown. In particular, this work is focused on the detector light collection system and on its upgrade concerning the wavelength shifting of the liquid argon scintillation from vacuum ultra-violet into visible light.

1. Introduction

The experimental observations of neutrino oscillations have established a picture consistent with the mixing of three neutrino flavours $\nu_e, \nu_\mu$ and $\nu_\tau$ with three mass eigenstates $\nu_1, \nu_2$ and $\nu_3$ whose mass differences turn out to be relatively small. However, in recent years, several experimental anomalies have been reported [1]. A possible phenomenological model with light sterile neutrinos is widely used in order to explain the anomalies in neutrino oscillation pattern described above: the so called 3+1 model. According to this model, the existing neutrino states are the three interacting lepton flavours and a fourth non-interacting sterile neutrino state. Global analysis of all the data relevant for the sterile neutrino hypothesis were performed. The results of the 3 + 1 global fit are reported in [2].

2. The SBN program

The Short-Baseline Neutrino (SBN) physics program [3], emerging from a European - US collaboration, will deliver a rich and compelling physics opportunity, including the possibility to investigate the experimental anomalies in neutrino physics and to perform the most sensitive search to date for sterile neutrinos at the eV mass-scale through both appearance
Figure 1. Map of the Fermilab neutrino beamline area showing the axis of the BNB (blue dashed line) and locations of the SBN detectors at 110 m, 470 m and 600 m.

and disappearance oscillation channels. The SBN program includes three Liquid Argon Time Projection Chamber (LAr-TPC) detectors (Fig. 1) namely the Short-Baseline Near Detector (SBND), Micro Booster Neutrino Experiment (MicroBooNE), and Imaging Cosmic And Rare Underground Signals (ICARUS) experiments, located on-axis along the Booster Neutrino Beam (BNB) line at Fermilab. The size and position of the three detectors allow to characterize the beam before oscillations in the near detector and to measure simultaneously $\nu_e$ appearance and $\nu_\mu$ disappearance in the MicroBooNE and ICARUS detectors.

3. The ICARUS T600 Time Projection Chamber

ICARUS T600 will act as the SBN far detector. It successfully operated at Gran Sasso National Laboratories (LNGS) on the CERN Neutrino to Gran Sasso (CNGS) muon neutrino beam from 2010 to 2012 and it was the first large scale LAr TPC to be exposed to a neutrino beam and the largest existing LAr TPC for neutrino physics [4].

It consists of a large cryostat split into two identical modules and filled with 760 tons of ultra-pure liquid argon. Each module houses two TPCs separated by a common cathode, with a drift length of 1.5 m. Ionization electrons, abundantly produced by charged particles along their path (6000 electrons/mm for minimum ionizing particles at an electric field $E_D = 500$ V/cm), are drifted under uniform electric field towards the TPC anode made of three parallel wire planes. A total of about 53000 wires are deployed, with 3 mm pitch, oriented on each plane at a different angles ($0^\circ$, $+60^\circ$, $-60^\circ$) with respect to the horizontal direction.

By appropriate voltage biasing, the first two wire planes (Induction-1 and Induction-2) provide signals in a non-destructive way, whereas the ionization charge is collected and measured on the last plane (Collection).

3.1. Geometrical reconstruction of an ionizing event in ICARUS T600

Charge signals on the TPC wire planes, from ionization electrons, allow to obtain three bi-dimensional pictures of the ionizing event in the plane normal to the drift direction [5]. The relative time of each ionization signal, combined with the electron drift velocity information ($v_D \sim 1.6$ mm/μs), provides the position of the track along the drift coordinate. A three-dimensional image of the events can then be reconstructed by combining the wire coordinates on each plane and the measured drift time, with a resolution of about 1 mm$^3$ (Fig. 2). The precise
3.2. The T600 light collection system
The future operation of the ICARUS T600 at shallow depth at Fermilab requires an improvement of the light collection system due to the higher cosmic muons rate background at shallow depth, in order to detect with full efficiency the prompt scintillation light from events with energy depositions down to ~ 100 MeV or even below. Moreover, the ICARUS light collection system, such as in most LAr detectors, is essential for generating a light-based trigger signal and identifying the time of occurrence of each interacting particle with high temporal precision. The new T600 light collection system consists of 90 × 8” PMTs for each TPC, involving a total of 360 PMTs. The photomultiplier tube model and placement have been selected in order to satisfy the main light collection system requirement as an high detection coverage and granularity and a fast response [7]. However, a further requirement has been considered. The PMT photocathode is sensitive to λ = 400 ÷ 420 nm wavelength light whereas the LAr scintillation light is emitted at λ = 128 nm. Therefore, the most efficient way to detect the scintillation light is to shift them to longer wavelengths where the PMT photocathode is sensitive. Tetra-Phenyl-Butadiene (TPB) is the most common wavelength shifter used in LAr experiments. It is a fluorescent organic chemical compound which radiates blue light with an emission spectrum peak at 430 nm wavelength. Generally, a thin layer of TPB is used to cover the PMT front surfaces or some internal sections of the detector.

4. The TPB as wavelength shifter: the evaporation system
A thin layer of TPB was deposited on the sensitive glass window of all the PMTs by a thermal evaporator available at CERN. It consists in a vacuum chamber housing two copper crucibles (Knudsen cells) connected to an external heating system which allows to increase their internal temperature. In high vacuum regime (few 10⁻⁵ mbar), TPB starts to evaporate at T ≈ 190°C. Through a small hole in the crucible lid, the TPB vapour diffuses in the vacuum chamber forming a thin film on the PMT surface, which is at room temperature. The evaporation system has been realized to be able to control the main evaporation process parameters. In particular, a thickness control system, consisting of a quartz crystal placed inside the vacuum chamber, an external oscillator and a thickness monitor, was used. The variation of the crystal oscillation frequency allows to measures the quantity (thickness) of material deposited on its surface. The monitor displays the coated thickness value both per time unit (Å/s) and integrated on the whole process. Moreover, in order to obtain a good thickness uniformity, the PMT was fixed
Figure 3. Schematic design of the evaporating chamber and PMT rotative support. The Knudsen cells are also shown in their location inside the vacuum chamber.

looking downwards with respect to the vertical direction by a dedicated rotating support fastened below the lid of the vacuum chamber (Fig. 3).

5. Quantum Efficiency measurements

The TPB coating uniformity is evaluated in terms of light yield conversion. For this reason, an optical device was set up allowing to measure the overall PMT and TPB Quantum Efficiency ($QE$), namely the ratio of the number of photoelectrons released in the photocathode to the number of photons absorbed by the wavelength shifter. Quantum efficiency is derived by the equation:

$$QE_{DUT}(\lambda) = QE_{NIST}(\lambda) \times \frac{I_{DUT}(\lambda) - I_{DUT dark}}{I_{NIST}(\lambda) - I_{NIST dark}}$$ (1)

where $QE_{DUT}$ and $QE_{NIST}$ are respectively the PMT under test and the calibrated photodiode (tabulated value) quantum efficiency, $I_{DUT}$ and $I_{NIST}$ are respectively the PMT and photodiode cathodic current values and $I_{dark}$ are the dark currents.

5.1. The optical system

The optical device used for the QE measurements is shown in Fig. 4. The light source is a Deuterium lamp whose emission spectrum has two peaks at 121 nm and 161 nm. The focusing elbow allows sending the deuterium lamp light to the Monochromator. Focusing is made by a UV-reflective mirror. The light generated by the deuterium lamp light gets into the monochromator through a first slit, which allows to calibrate its intensity. A diffraction grating (120 ridges/mm) and a second slit allow to select the light wavelength and to regulate its range amplitude. A collimation system, consisting of two different collimator, allows to stabilizes the light beam size and to reduce its divergence. The light beam is sent towards a rotative mirror which allows to selectively direct it towards the PMT or the calibrated photodiode. The cathodic current from both the photomultiplier and the photodiode is alternately measured by a pico-ammeter.
5.2. Measurements and results
The coating uniformity on the PMT sensitive window has been evaluated in terms of light yield conversion. To this purpose, the PMT was fixed inside the measuring chamber by means of a specific support ring, which allows to rotate the photomultiplier perpendicularly to its own axis. At first, the PMT response on its window center at $\lambda = 128$ nm was measured. After that, PMT was rotated in the horizontal plane with an angle between $-40^\circ$ and $+40^\circ$ with respect to the optical beam axis, in steps of $5^\circ$. In this way, the PMT response was measured along a radius of the photomultiplier window. This measure was repeated after rotating the PMT around the optical axis respectively of $90^\circ$, $45^\circ$ and $-45^\circ$. Results are shown in Fig. 5. The PMT response spectrum as a function of the incident light wavelength is also shown.

Test was repeated comparing the Quantum Efficiency response of other PMTs along one circle, only. Results, also showing a mainly flat response, are displayed in Fig. 6.

Figure 4. Experimental set-up of the optical device used for the Quantum Efficiency measurements.

Figure 5. Results of the uniformity test on a photomultiplier. In a) the resulting overall Quantum Efficiency is shown on 4 different axis on the PMT surface. In b) the PMT response spectrum as a function of the incident light wavelength is also shown.
Figure 6. Results of the uniformity test on 5 PMTs. The resulting QE is shown ranging from 0.05 to 0.2.

Figure 7. Resulting distribution of the coating densities of the mylar samples. Each sample is related to a PMT evaporation run of the series production. In addition, 5 more PMTs were coated as spare.

6. Conclusions
The obtained evaporation technique was used to coat with the TPB all the 360 PMTs constituting the new ICARUS T600 light collection system. In every PMT evaporation run, a mylar sample was fixed inside the vacuum chamber in a dedicated support in order to check the coating density as in the preliminary phase. The resulting distribution of the coating densities related to all the PMTs of the series production is shown in Fig. 7. The measured Quantum Efficiency response all over the PMT sensitive window is rather flat. This demonstrates the good reliability of the adopted evaporation technique, which allows to obtain the best uniformity in terms of coating thickness and light yield conversion.

References
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