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Optical characterization of the JUNO liquid scintillator

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Summary. — The JUNO experiment is a large liquid scintillator neutrino detector designed to determine the neutrino mass ordering with a sensitivity of 3-4 σ in 6 years. JUNO is a huge detector under construction in the southern part of China. The active mass of the JUNO detector will be 20 kton of organic liquid scintillator, which converts the released energy, causes by a neutrino interaction, into visible light. The fluorescence light propagates for about 17.5 m, for an event at the center of the detector, before it is converted in electric signal by 17612 20-inch PMTs and 25600 3-inch PMTs.. Given the high mass of the detector and the high resolution required to determine the neutrino mass ordering (3% at 1 MeV), having an accurate description of the liquid scintillator in the JUNO Monte Carlo is mandatory. For this reason, at the Universitá degli studi di Milano, we built two small scale experiments to measure the emission time profiles for different particles and the light propagation measuring both the refractive index and the group velocity in the liquid scintillator.

1. – Jiangmen Underground Neutrino Observatory

The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino detector under construction in China [1]. JUNO will be a multi-purpose experiment detecting neutrinos from different sources. The main goal is to determine the neutrino mass ordering with six year of data-taking, but it can also improve the current best measurement on the oscillation parameters, solar neutrino fluxes [2] and it can detect Supernova neutrinos in real-time in case of an explosion [3]. JUNO will detect neutrinos using 20 kton of an organic liquid scintillator composed by three elements. Linear alkyl benzene (LAB) is the organic solvent in which 2.5 g/L of PPO is dissolved, acting as fluoride, and 3 mg/L of bis-MSB acting as wavelength shifter to increase the attenuation length in the detector. The emitted light needs to travel more than 17 meters in the liquid scintillator, for an event at the center, to be detected by the 17612 20-inch and 25600 3-inch PMTs [4]. The detector commissioning will start at the end of 2024.

2. – Time of light emission measurements: the SHELDON-project

To reach the energy resolution (3% at 1 MeV) and the position resolution (7 cm at 1 MeV) required to determine the neutrino mass ordering a full and accurate characterization of the optical parameters is mandatory. For this reason many groups in the JUNO collaboration started to built small scale experiments to measure separately these parameters. In this contest, in the university of Milan (Universitá degli Studi di Milano) the JUNO-Milano group built two experimental setup, called SHELDON([1]) and Rewind([2]), to accurate measure different optical parameters of the JUNO liquid scintillator [5].

2˙1. *Fluorescence measurements.* – Using the well known Time-Correlated Single Photon Counting (TCSPC) technique it is possible to measure in a small quartz cell (3x3x3 cm^3) the emission time of liquid scintillators [6]. In particular, in the Milan setup, we have two photomultiplier tubes (PMTs), one in single photon counting mode and the other used to trigger events. The signals of these PMTs go to two 5 Gsamples/s digitizers which acquire the arrival time and the amplitude of the electronic signals with a time resolution of 430 ps. Making the difference of the two signals it is possible to measure the emission time profiles. The fluorescence time profiles are important especially for two reasons. The first is the position reconstruction, since it is based on the arrival times of the scintillation photons on the JUNO PMTs. Hence to reconstruct the correct position of an event, in such a big detector, it is mandatory to have an accurate description of the emission times, which are not instantaneous, but could take up to hundreds nanoseconds. The second important reason of studying the emission time profiles is the particle identification using the pulse-shape discrimination (PSD) technique [6]. Since, as example, the solar neutrino signal is a beta-like event (solar neutrinos scatter on electrons) it is, a priopri, indistinguishable from the radioactive backgrounds like alpha particle. This because both of this events causes an emission of scintillation photons by the JUNO liquid scintillator. Looking to the fluorescence time profile it is possible to distinguish alpha from beta particles. Since the higher is the ionization of a particle the higher is the numbers of photons emitted after long times. This can be seen in our measurements using two radioactive sources ^{60}Co, to measure beta-like events, and ^{244}Cm, to measure alpha particles (fig. 1(a)). The fluorescence time profile of an organic liquid scintillator is usally described as a linear combination of four exponential with different characteristic decay constants. In SHELDON we use a fitter which convolves the fluorescence time profile model with the impulse response function of our experimental setup in order to extract times (τ_i) and weights (q_i) of the fluorescence linear combination:

$$F_{fluo}(t) = \sum_{i=1}^{4} \frac{q_i}{\tau_i - \tau_r}(e^{-t/\tau_i} - e^{-t/\tau_r}). \tag{1}$$

Our results, show in table I, on fluorescence time profile are obtained on the linear alkyl benzene processed by the distillation plant during its commissioning. This are the first fluorescence time profile measurements on it and they are promising for the alpha-beta discrimination in the JUNO experiment.

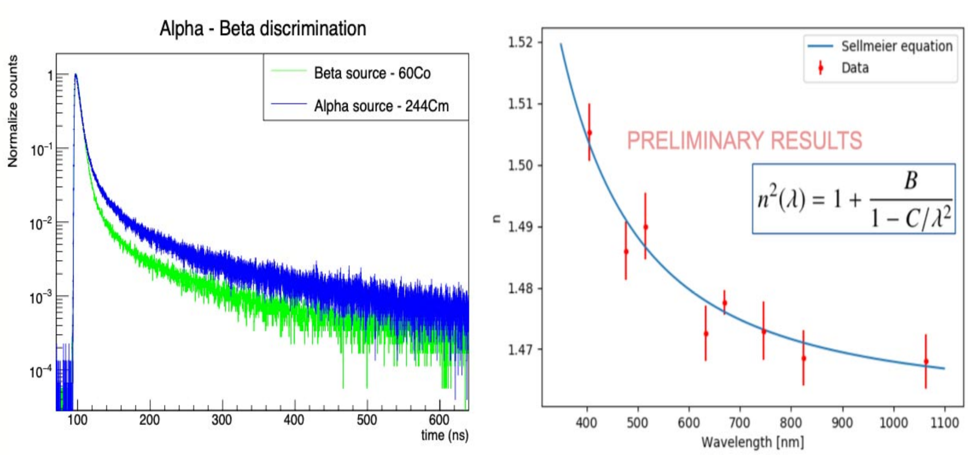
([1]) Separation of cHErenkov Light for Directionality Of Neutrinos.
([2]) REfractive index With INterferometric Devices.

TABLE I. – *Results of the fit of fluorescence time profile of the JUNO liquid scintillator samples with alpha and beta sources with only statistical errors.*

	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]	τ_4 [ns]
α	4.24 ± 0.02	18.51 ± 0.41	96.42 ± 2.1	653 ± 11
β	3.61 ± 0.01	16.64 ± 0.38	85.6 ± 2.3	573 ± 12
	q_1 [%]	q_2 [%]	q_3 [%]	q_4 [%]
α	53.50 ± 0.30	24.64 ± 0.21	13.93 ± 0.14	8.80 ± 0.39
β	77.46 ± 0.25	12.17 ± 0.16	6.45 ± 0.15	4.23 ± 0.33

3. – Measurement of the refraction index: the Rewind project

An other optical property which is mandatory to study in order to understand the propagation of light in the liquid scintillator and so the position reconstruction is the refraction index of the medium. Since the JUNO liquid scintillator has a very high absorbance below 400 nm, for the aims of measuring the speed of light in the detector we investigate the wavelength above that number. We use a refractometer to measure the refraction index. It is composed by a laser source which pass into a quartz cell (optical path 1 cm) to a camera (CCD). Filling the cell with the liquid scintillator it will produce a shift in the laser beam and this will turn out in a displacement on the camera. Looking to that it is possible to extract the refraction index on the medium. We calibrate this apparatus using well refractive index and monitoring the temperature, we always use water as reference to determine the incident angle of the laser beam on the cuvette. Then changing the laser and the selected wavelength we measured the refractive index at eighth different wavelength to extract the Sellmeier equation, which can be used to



(a) (b)

Fig. 1. – (a) Fluorescence time profiles of the JUNO liquid scintillator with alpha and beta sources. (b) Refractive index of the JUNO linear alkyl benzene at different wavelengths.

TABLE II. – *Results of the refractive index of linear alkyl benzene.*

Wavelength [nm]	405.5	476.5	514.5	633
Refractive index	1.505 ± 0.007	1.486 ± 0.007	1.490 ± 0.008	1.473 ± 0.007
Wavelength [nm]	670	745.5	823.5	1064
Refractive index	1.478 ± 0.003	1.473 ± 0.007	1.469 ± 0.007	1.468 ± 0.007

describe the refractive index in the optical region for these liquids:

$$n^2(\lambda) = 1 + \frac{B}{1 - C/\lambda^2}. \tag{2}$$

4. – Conclusions and prospectives

In this work it is shown how the Milan group of the JUNO collaboration measured two important properties of the JUNO liquid scintillator. This measurements will improve the event reconstruction in JUNO increasing the position reconstruction and the particle identification. The Milano group is also working to measure other two important quantities. First the amount of Cherenkov light produced in the JUNO liquid scintillator, this has an impact on on the energy resolution and should be tuned in the JUNO Monte-Carlo. The second is the group velocity which will impact on the position reconstruction and on the simulation of the Cherenkov light propagation.

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