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Characterization of the JUNO liquid scintillator optical properties

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Summary. — The Jiangmen Underground Neutrino Observatory, JUNO, is a massive neutrino experiment located near Kaiping, in south China, that will exploit organic liquid scintillator (LS): a mixture of linear alkyl benzene (LAB), 2.5 g/L of 2,5 diphenyloxazole (PPO) and 3 mg/L of 1,4-Bis(2-methylstyryl)benzene (bis-MSB). Thanks to its large mass (20 kton target of LS) and its high energy resolution (3% at 1 MeV), JUNO will be a cutting-edge experiment in neutrino physics, with the main goal of determining the Neutrino Mass Ordering (NMO). In order to do that it is fundamental to fully understand the detector response by characterizing the optical properties of the scintillator. This work reports the study conducted by the JUNO-Milano group on the emission, absorption, fluorescence time profiles, refractive index and velocity group of the JUNO LS.

1. – Introduction

Neutrinos have mass, however the relative ordering of their mass eigenstates (m_1, m_2 and m_3) is still unknown. We know that $m_1 < m_2$ [1], but there are no information on m_3, giving two possible solutions: the *Normal Ordering* ($m_1 < m_2 < m_3$) and the *Inverse Ordering* ($m_3 < m_1 < m_2$). Determining the NMO is fundamental to understand important properties of neutrino, making it one of the main goal of the JUNO experiment.

In order to do that, JUNO will exploit the oscillation effect [2] of reactor anti-neutrino $\overline{\nu}_e$, coming from Yangjiang and Taishan Nuclear Power Plants ($\sim$ 53 km distant from JUNO site) [3]. Since $\overline{\nu}_e$ changes flavor on the way from the reactor to JUNO central detector, the original $\overline{\nu}_e$ energy spectrum is deformed in two different ways, depending on the NMO. To be sensible to this extremely little difference an high energy resolution is required. The detection process in JUNO is based on the emission of light caused by the interaction of particles with its scintillator. To reconstruct the event vertex and the particle energies, it is crucial to fully understand the detector response and how photons propagate before reaching the phototubes (PMTs). For this reason a characterization of the optical properties of the JUNO LS is mandatory. In order to do that, the JUNO-Milano group exploited the SHELDON facility to study the absorption, fluorescence time profiles, refractive index and group velocity of the JUNO LS. Thanks to the contribution of the Università di Perugia, it was also possible to study the JUNO LS emission.

2. – Emission

The JUNO LS, is a mixture of LAB, the solvent, 2.5 g/L of PPO, the "primary wavelength shifter" (scintillating component), and 3 g/L of bis-MSB, the "secondary wavelength shifter" (it shifts the emission to higher wavelengths). This recipe was accurately chosen to match the quantum efficiency (Q.E.) of the PMTs. In order to verify this statement and study the detector response, an emission spectrum measurement is mandatory. This study was made exploiting a Spex Fluorolog-2 1680/1 spectrofluorimeter. This instrument excites a small LS sample (1 cm-path length cuvette) with a 260 nm light and then it samples its emission. The left plot of fig. 1 shows the resulting emission spectrum which is dominated by the bis-MSB contribution (400 nm and 420 nm peaks). However, at this scale, it is also possible to notice the residual contribution of PPO (360 nm peak). As expected the JUNO mixture matches well the 20″ PMTs Q.E. [4].

3. – Absorption length

The scintillator not only emits photons, but it can also absorb them. Since the number of photons reaching the PMTs is fundamental for the energy reconstruction, it is important to know JUNO LS absorption length, *i.e.*, the mean free path of the light in the scintillator. The absorption length L_A cannot be measured directly, however it can be derived from the absorbance A (eq. (1)), which is an index of the amount of light absorbed in the medium, depending on the optical path length x

$$L_A = \frac{x \cdot \log_{10} e}{A}. \tag{1}$$

The SHELDON facility is equipped with a Jasco V-760 Spectrophotometer provided with a LSE-701 Single Position Long Path Length Cell Holder (maximum holder length: 10 cm). For a given wavelength range, this instrument allows to compare the light absorbed by a sample with respect to a second one, used as a baseline. It has been decided to use hexane as baseline, due to its high transparency and for having a refractive index similar to the JUNO LS one, which allows to reduce unwanted reflection and refraction effects. In order to extend the sensibility to a wider range of absorption length, the measurements have been conducted using cuvettes of different path lengths (1 cm, 5 cm and 10 cm). The resulting absorbances have been converted using eq. (1) and combined to obtain the absorption length mean trend shown in the right plot of fig. 1.

4. – Fluorescence time profiles

The event position reconstruction requires to measure the photon arrival times to the PMTs. In order to do that it is first necessary to understand the timing with which the photons are emitted. In particular the time distribution of the fluorescence light emitted by a LAB-based liquid scintillator can be modelled as a superposition of four decreasing exponential contribution [5] with characteristic time constants τ_i and relative weight q_i, as described in eq. (2) (where τ_r is the characteristic rise time)

$$F_{fluo}(t) = N \sum_{i}^{4} \frac{q_i}{\tau_i - \tau_r} \left(e^{-\frac{t}{\tau_i}} - e^{-\frac{t}{\tau_r}} \right). \tag{2}$$

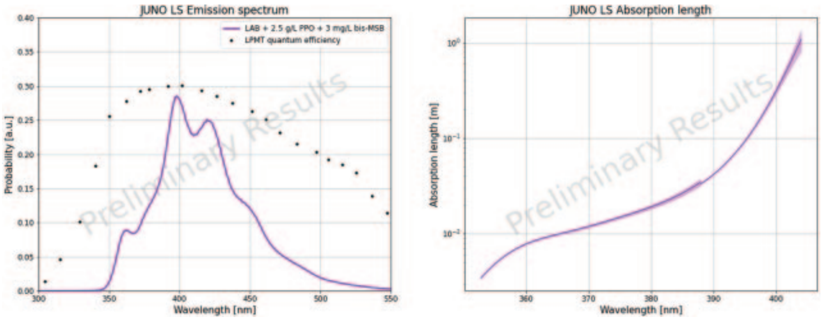

Fig. 1. – The left plot shows the preliminary results on JUNO LS emission spectrum (in violet solid line) and JUNO Large NNVT-PMT (LPMT) quantum efficiency (black dots) [6]. The right plot shows the preliminary results on JUNO LS absorption length trend with 5σ error bar [6].

In order to measure the fluorescence time profiles, the SHELDON facility exploits the Time-Correlated Single Photon Counting Technique [5] in which a small sample of JUNO LS ($\sim$ 3 cm^3) is seen by two PMTs, one strongly coupled and the other weakly coupled to the scintillator. This setup allows to measure the τ_i generated by different sources. In particular, we have studied the fluorescence profiles induced by α and β radiations (obtained using ^{244}Cm and ^{60}Co sources respectively). The results are shown in the left plot of fig. 2 and the values of τ_i and q_i are listed in table I: as expected, the time profiles emitted by α and β are different especially in the tail and this will be used in JUNO to discriminate signal from background (Pulse Shape Discrimination Technique [7]).

5. – Refractive index and group velocity

In order to properly reconstruct the event vertex it is fundamental to understand how the emitted photons propagate in the LS medium. This information depends on JUNO LS refractive index n and group velocity v_G. For this analysis the SHELDON facility has been equipped with a table-top experimental setup [8] which consists of a refractometer

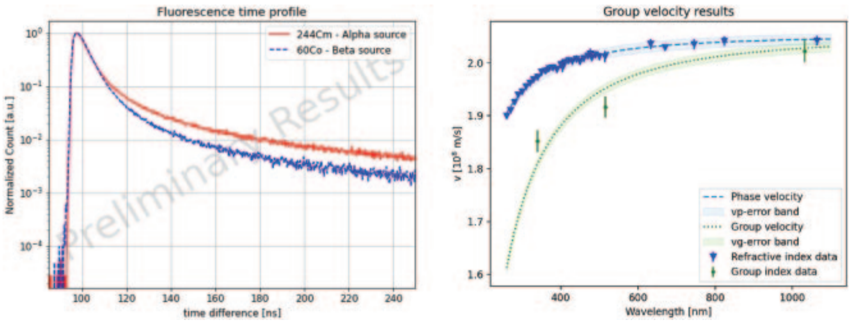

Fig. 2. – The left plot shows the preliminary results on the fluorescence time profile of the JUNO LS induced by an α source (in red solid line) and a β source (in blue dashed line) [6]. The profiles are normalized at the maximum. The right plot shows JUNO LS phase velocity (blue) and group velocity (green) results [8].

Table I. – *Best estimation of the α and β fluorescence time parameters for JUNO LS.*

	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]	τ_4 [ns]
α	4.06 ± 0.01	17.29 ± 0.17	91.3 ± 1.1	598 ± 6
β	3.86 ± 0.02	14.52 ± 0.25	81.3 ± 1.8	570 ± 10

	q_1 [%]	q_2 [%]	q_3 [%]	q_4 [%]
α	54.04 ± 0.17	23.70 ± 0.14	14.06 ± 0.09	8.92 ± 0.26
β	67.79 ± 0.35	20.01 ± 0.27	7.53 ± 0.11	5.03 ± 0.50

(for n measurement) and a Michelson interferometer (for v_G measurement). The n study was performed by the JUNO-Milano group in the wavelength range from 400 nm to 1064 nm. The results have been compared and validated with the ones obtained by a group in IHEP within the JUNO Collaboration, who measured n from 260 nm to 500 nm with an ellipsometer [8]. For what concerns the v_G study, the measurements have been made using three different wavelengths: 340 nm, 516 nm, and 1036 nm. The results on v_G are shown on the right plot of fig. 2 [8]. The plot also shows the phase velocity curve (blue) determined as the ratio between the speed of light and n.

Note that, since the concentration of PPO and bis-MSB in JUNO LS are very low, all measurements have been conducted on a sample (few cm^3) of pure LAB.

6. – Conclusion

The aim of this work was to provide an accurate characterization of the optical properties of the JUNO LS, based on a small scale analysis (of the order of few cm^3). In particular this work reports the results obtained by the JUNO-Milano group on the analysis of the emission, refractive index, group velocity, absorption and fluorescence time profiles of JUNO LS. These results will be fundamental to build a reliable Monte-Carlo code that will ensure the optimal energy and position reconstruction required for the NMO determination in JUNO.

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