IL NUOVO CIMENTO **46 C** (2023) 67
DOI 10.1393/ncc/i2023-23067-0

Communications: SIF Congress 2022

The JUNO detector and its liquid scintillator optical properties

G. Reina
INFN, Sezione di Milano, Dipartimento di Fisica, Università di Milano - Milan, Italy

received 6 February 2023

Summary. — The Jiangmen Underground Neutrino Observatory (JUNO) is a multiporpose neutrino experiment currently in construction in China. It is designed to determine the neutrino mass ordering, to precisely measure the oscillation parameters, to perform solar neutrino spectroscopy and to study supernova neutrinos and geoneutrinos. JUNO's Central Detector holds 20 kton of liquid scintillator (LS), as target mass. The LS is contained in a huge acrylic sphere of 35 m in diameter, which is equipped with more than 43000 photomultipliers tubes (PMTs). The acrylic sphere is supported by a stainless-steel structure. A Cherenkov water pool and a Top Tracker, as veto detectors, are added to the total structure. The liquid scintillator is the main core of JUNO, since it is the interacting target of the neutrinos. Therefore, it is essential to know its optical properties in details. In particular, the scintillator refractive index and the group velocity play a crucial role in the photon propagation and need to be measured with high precision.

1. – Introduction

The flavour oscillation of neutrinos is well established from the observation of several neutrino experiments, leading to the conclusion that neutrinos have non-zero mass. Neutrinos absolute masses are currently unknown and neutrino oscillations experiments are sensitive to Δm^2_{ij}, which is the difference of the square values of the mass eigeinvalues m_i and m_j. Nowadays, the best values of Δm^2_{21}, $|\Delta m^2_{23}|$ and $|\Delta m^2_{31}|$ obtained by a global fit of all neutrino experiments performed are about 7.42×10^{-5} eV^2, 2.51×10^{-5} eV^2 and 2.50×10^{-3} eV^2, respectively [1]. However, the relative ordering of m_1, m_2 and m_3 is still an open fundamental question of the neutrino physics and goes by the name of Neutrino Mass Ordering (NMO). There are two possible orderings: normal (NO), where m_3 is higher than m_1 and m_2, and inverted (IO), which is the opposite [2].

The main goal of JUNO is the determination of the NMO, along with the precise measurement of flavour oscillation parameters, the study of neutrinos from the Sun, the Earth and Supernovae.

JUNO is a liquid scintillator based detector, currently in construction in China, which will start the data taking in 2024. The core of JUNO is a large amount (20 kton) of liquid scintillator. Antineutrinos and neutrinos which arrive to the core of the detector interact

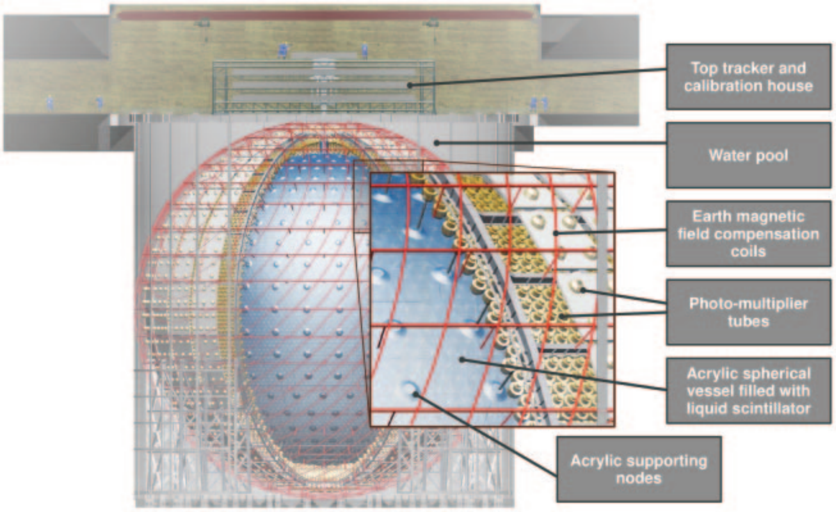

Fig. 1. – Design of the JUNO detector structure [3].

with the LS, producing charged particles which deposit energy in the medium, emitting light. The light is eventually collected by PMTs: in first approximation, the energy of each event is proportional to the number of collected photons, while the interaction vertex position can be determined from the arrival times of the photons to the PMTs.

The JUNO source for the determination of the NMO are reactor antineutrinos emitted from two power plants located at a distance of 52.5 km from the detector. This is the distance at which the difference between the two possible orderings is maximized.

To reach the main goal of JUNO an energy resolution of 3% at 1 MeV and a spatial resolution of 10 cm at 1 MeV are required [4]. Moreover, the events of interest must be correctly identified with a proper event reconstruction, which strongly depends on the LS properties. Thus, the characterization of the scintillator optical properties is a crucial element for the success of the experiment.

Here, I will focus on the measurements of the refractive index as a function of the wavelength and of the group velocity. The first parameter influences the energy and vertex reconstruction, along with their resolutions, while the second one impacts on the vertex reconstruction. These measurements are performed by the Milano group.

2. – JUNO detector

2˙1. *JUNO overview.* – The JUNO detector system consists of a Central Detector (CD), of a water Cherenkov detector pool and of a Top Tracker (TT). The CD includes a 20 kton of liquid scintillator contained in an acrylic vessel with an inner diameter of 35.4 m, which is immersed in the water pool. The vessel is then supported by a stainless-steel structure, whose inner surface is equipped with more than 43000 PMTs. The water pool contains 2400 PMTs to detect the Cherenkov light from cosmic muons, acting as a veto detector. On top of the water pool, the TT, made of a plastic scintillator array, works as an another veto detector to accurately identify the muon tracks. Moreover, the experimental site is covered by a shield of 700 m of rocks to reduce the cosmic background [2]. A picture of the detector structure is shown in fig. 1.

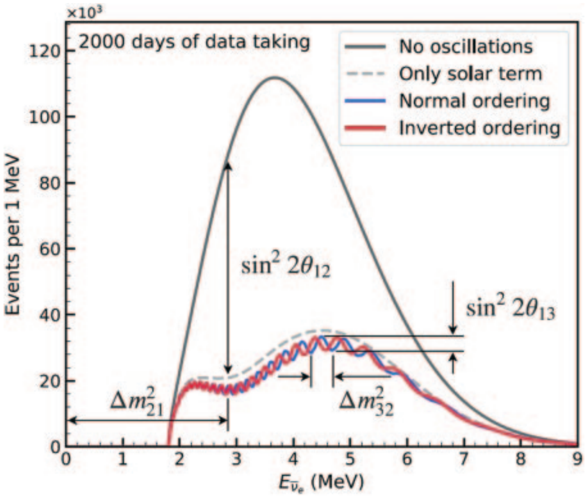

Fig. 2. – Simulated reactor antineutrinos energy spectrum in JUNO at a baseline of 52 km in 5 years and a half. The spectrum shows two trends depending on the two possible orderings: normal, in blue, or inverted, in red.

2˙2. *Liquid scintillator*. – The LS is the main core of the JUNO experiment and it is the target of the particles of interest. The chemical recipe is purified Linear Alkyl Benzene (LAB) as solvent, 2.5 g/L of 2,5-diphenyloxazole (PPO) as fluor, and 3 mg/L of 1,4-bis(2-methylstyryl)benzene (bis-MSB) as wavelength shifter.

Particles that deposit energy in the LS excite its molecules. The transition from the excited levels to the ground state causes the emission of light, called fluorescence light. The light yield and the times of this process depend on the liquid scintillator itself. The light yield of JUNO LS is about 10^4 photons/MeV and the emission spectrum is extended from 300 nm to 550 nm, showing a peak around 430 nm, while the fluorescence times go from few ns to few μs [2].

3. – The antineutrino detection in JUNO

The determination of the NMO in JUNO is achieved by studying the energy spectrum of reactor antineutrinos which interact with the LS.

Reactors emit electronic antineutrinos $\bar{\nu}_e$ with energy from 1 MeV to 10 MeV. At these energies, the $\bar{\nu}_e$ passing through the LS can interact via Inverse Beta Decay (IBD): the $\bar{\nu}_e$ interacts with a proton of the medium, producing a positron and a neutron. The first one annhilates with an electron of the medium after few ns, producing two back to back 511 keV photons (prompt signal); the latter scatters and after about 200 μs get absorbed by a proton of the medium, emitting gamma rays of 2.2 MeV energy (delayed signal). The spatial, time and energy coincidence of the prompt and delayed signals identifies the IBD event.

The distance of 52 km that reactor antineutrinos travel before they interact with the LS is a peculiar characteristic, which allows the distinction of the two possible ordering scenarios at best.

The energy spectrum of reactor antineutrinos in JUNO, obtained by simulations, is derived by the convolution of the reactor antineutrino flux and the IBD cross section and it is shown in fig. 2 [2]. Antineutrinos oscillate during their way to the LS, and this affects the antineutrino flux observed in JUNO, resulting in an oscillated spectrum. Moreover, as can be seen in the fig. 2, the spectrum can assume two different shapes, depending on whether the neutrino mass ordering is normal, in blue, or inverted, in red.

With the energy resolution expected in JUNO, it is possible to distinguish the subtle difference in the energy distribution, determining the NMO. In order to do so, it is crucial to recognize the events of interest. In such a context, it is necessary to provide the correct model for the energy and vertex position reconstruction. The first one is the key to the determination of the NMO since it defines the observed energy spectrum, while the latter is very important to increase the signal-to-noise ratio, by removing external backgrounds, selecting only events in an innermost fiducial volume.

4. – Energy and vertex reconstruction

Particles that deposit energy in the liquid scintillator yield optical photons which result in PMT signals. These signals come from the number of photoelectrons (nPE) generated by the photons hitting the PMTs. The nPE strongly depends on the absolute scintillation yield, on the attenuation of the propagation inside the medium, and on geometrical effects. The output signals carry information on the total number of collected photons and their arrival times to the PMTs. These quantities allow the reconstruction of the energy and vertex position of an event.

The reconstructed energy is estimated by a maximum likelihood fit algorithm and it is strictly linked to the total nPE generated: the higher is the number of photoelectrons registered, the higher is the energy of the event [5]. However, this relation is not straightforword. Some effects influence the linearity, such as the quenching and the Cherenkov effect. The first one refers to any process which decreases the fluorescence intensity, particularly at low energies; the latter occurs when a charged particle is faster than light inside the medium, causing the emission of Cherenkov photons. The charged particle loses its energy along its way in the LS and eventually will not be able to emit Cherenkov photons. Since this is a threshold effect, the direct proportionality between nPE and the energy event no longer applies. In addition to this, a worsening of the energy resolution occurs. Hence, a correct estimation of the quenching parameters and the Cherenkov contribution is needed.

The position where the neutrino has interacted in the scintillator can be obtained by a fit of the arrival time of the photons at each PMT [6].

The total number of collected photons and their arrival times strongly depend on the properties of the LS. Specifically, the total number of collected photons mostly depend on the scintillation light yield, on the transparency of the scintillator, and on the Cherenkov contribution; while the arrival times mostly depend on the absorption and re-emission, on the Rayleigh scattering, on the refraction and total internal reflection, and on the Cherenkov process.

All these properties of the LS strongly affect the energy and spatial resolution and the event reconstruction, which must be accurate to correctly identify the event of interest. To this purpose, the best LS characterization is needed. There is a strong effort within the JUNO Collaboration to collect all these information on the LS. The group of Milan is particularly involved in this research.

In the following sections, I will focus on the measurement of the liquid scintillator refractive index and of the group velocity performed in Milan, along with their importance for the JUNO experiment.

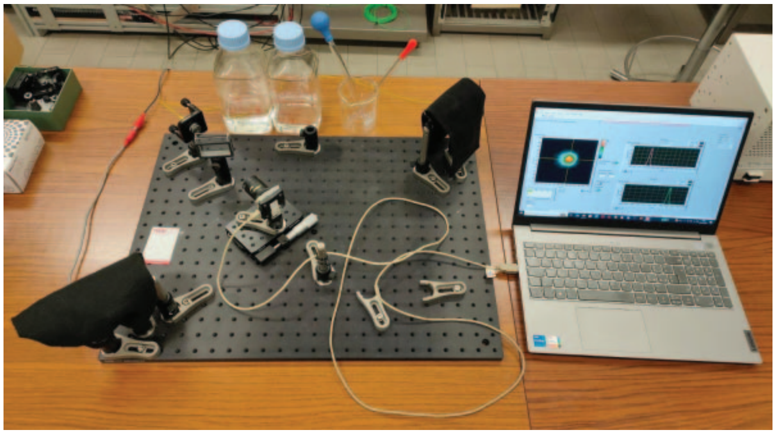

Fig. 3. – Experimental setup of the refractometer. It consists of a laser source, of a cuvette, of a CCD camera and of a DAQ code. The light is propagated passing through several devices: filters, collimators and optical fibers.

5. – Refractive index

The knowledge of the refractive index n of the LS as a function of the photon wavelength is needed to provide a correct vertex and energy reconstruction.

The velocity of light inside the LS is reduced and can be described introducing the refractive index of the medium. This effect influences the photons arrival times to the PMTs, and, consequently, the position reconstruction. Moreover, the Cherenkov contribution, which influences the energy reconstruction and resolution, is estimated to be about 1% of the total light emitted by the LS and depends on n, as can be seen in the Frank-Tamm Formula 1.

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right). \tag{1}$$

For these reasons, a precise measurement of n is fundamental. In Milan, we use a refractometer setup with several light sources to measure this parameter as a function of the wavelength.

A refractometer is a laboratory device which allows the measurement of the refractive index of a material. It consists of a source, of a photosensor and of a support for the sample of the material of interest, which is the LS. The insertion of the LS between the source and the photosensor causes a displacement of the beam due to the changing of the refractive index along the beam path. The displacement is obtained by measuring the difference of the beam positions when the cuvette is empty or filled with LS. Since it depends on the material, we can extract the refractive index of the LS.

The experimental setup that we use consists of several laser sources, with wavelengths extending from 1035 nm to 258 nm, of a cuvette of quartz with a 0.966 mm width used to contain the sample of LS, of a DCC1545M camera [7] with 1280 × 1024 pixels with a sensitive sensor of 5.2 μm per pixel, of a LabView2022 code for the acquisition, and of other components for the correct propagation of light from the source to the CCD. This experimental setup is shown in fig. 3.

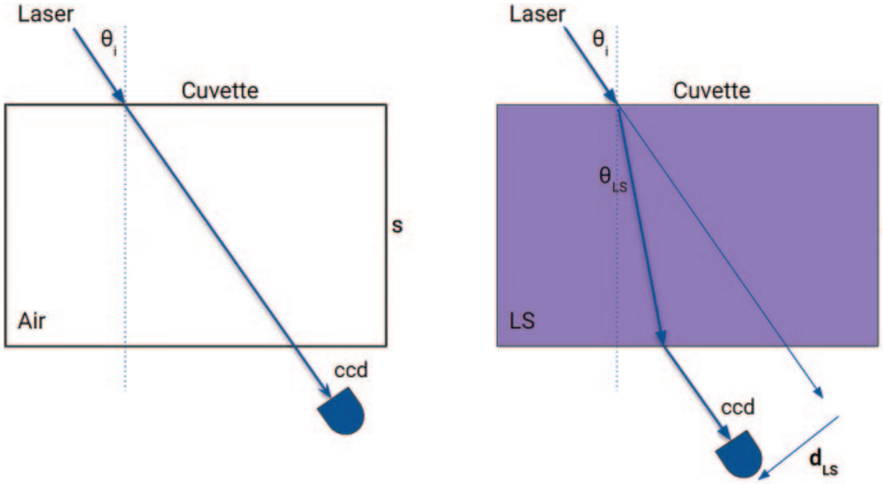

Fig. 4. – The presence of the LS between the source and the CCD causes a deflection of the beam with respect to the initial direction. The deflection results in a difference beam position on the CCD. By measuring the difference of the beam position, the displacement is obtained and the refractive index of the LS can be extracted.

A schematic view of the experimental procedure is shown in fig. 4.

The displacement d_{LS}, obtained by the Snell's law and geometrical construction, is

$$d_{LS} = \frac{s \sin\left[\theta_i - \arcsin(\frac{n_{air}}{n_{LS}} \sin\theta_i)\right]}{\cos\left[\arcsin(\frac{n_{air}}{n_{LS}} \sin\theta_i)\right]}, \tag{2}$$

where s is the width of the cuvette, θ_i is the incident angle of the beam on the cuvette, n_{air} and n_{LS} are the refractive indeces of air and of the LS, respectively.

It is worth noting that the perpendicularity of the beam to the CCD's plate is a necessary condition to use this formula.

As shown in eq. (3), the displacement d_{LS} strongly depends on θ_i. Since this parameter relies on the orientation of the cuvette, which is difficult to estimate, we use a material with well-known refractive index to measure it. This calibration is done filling the cuvette with pure H_2O. Since its refractive index is well known, it is possible to extract the value of θ_i from a measurement of the displacement caused by the presence of the water inside the cuvette.

Once all the information is available, it is possible to measure n_{LS} with a relative uncertainty at a subpercent level.

6. – Group velocity

As said before, the vertex position reconstruction relies on the arrival time of photons to the PMTs, which depends on the propagation velocity of photons inside the LS. In particular, since the PMTs do not detect the wavelength of photons, the group velocity is needed in order to have a reliable Monte Carlo simulation of the JUNO detector [8].

A proper characterization of the propagation of light inside the medium highly improves the simulations.

The scintillation photons are emitted with a characteristic emission spectrum wavelengths. Hence, the correct way to predict the light propagation inside the LS should involve the group velocity, V_g defined as follows:

$$V_g = V_p \left(1 - \frac{\lambda}{n}\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right)^{-1}, \tag{3}$$

where V_p is the phase velocity, λ is the wavelength and n is the refractive index.

We use an interferometer to measure V_g. An interferometer consists in a laser producing a wave package, which is splitted by a beam splitter, and propagated to two reflecting mirrors. Once reflected, the package overlaps with itself, causing interference. The overlapped package is detected with a photosensor. If a LS sample is inserted in one arm of the interferometer, a difference on the travel time of the package occurs. This difference in time can be bridged with a shift of the mirror present in the arm containing the LS. By measuring this shift, one obtains the V_g.

The experimental setup is currently under development.

7. – Conclusions

JUNO will be a flagship detector for the neutrino physics, with the determination of the NMO as its main goal. In order to do so, high energy and spatial resolution are required, along with a proper model for the event reconstruction. These requirements need an accurate characterization of the properties of JUNO's liquid scintillator.

The group in Milan is very involved in this research, performing precise measurements of the liquid scintillator refractive index and of the group veocity. These parameters will have a crucial impact on the energy and vertex position reconstruction of the events.

REFERENCES

[1] Esteban I., Gonzalez-Garcia M. C., Maltoni M., Schwetz T. and Zhou A., *JHEP*, **2020** (2020) 178.
[2] JUNO Collaboration, *Prog. Part. Nucl. Phys.*, **123** (2022) 103927.
[3] Abusleme A. *et al.*, *Chin. Phys. C*, **46** (2022) 123001.
[4] An Fengpeng *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **43** (2016) 030401.
[5] Wu W., He M., Zhou X. and Qiao H., *JINST*, **14** (2019) P03009.
[6] Liu Q., He M., Ding X., Li W. and Peng H., *JINST*, **13** (2018) T09005.
[7] `https://www.thorlabs.com/thorproduct.cfm?partnumber=DCC1545M`.
[8] On behalf of the JUNO Collaboration (Lin T., Zou J., Li W., Fang X., Cao G., Huang X. and You Z.), *J. Phys.: Conf. Ser.*, **898** (2017) 042029.