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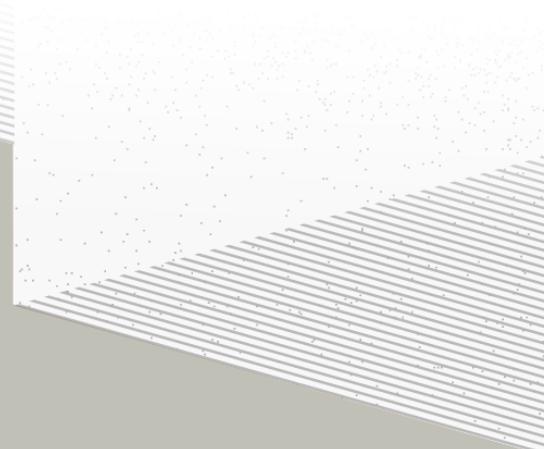
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Par

Léonard Imbert

**Precision measurement of solar neutrino oscillation parameters
with the JUNO small PMTs system and test of the unitarity of the
PMNS matrix**



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³ List of Abbreviations

ACU	Automatic Calibration Unit
CD	Central Detector
CLS	Cable Loop System
GT	Guiding Tube
IBD	Inverse Beta Decay
IO	Inverse Ordering
JUNO	Jiangmen Underground Neutrino Observatory
LPMT	Large PMT
LS	Liquid Scintillator
NMO	Neutrino Mass Ordering
NO	Normal Ordering
PE	Photo Electron
PMT	Photo-Multipliers Tubes
ROV	Remotely Operated under-LS Vehicle
SPMT	Small PMT
TR Area	Total Reflexion Area
TTS	Time Transit Spread
TT	Top Tracker
WCD	Water Cherenkov Detector

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⁴⁸ **Remerciements**

⁴⁹ Introduction

⁵⁰ **Chapter 1**

⁵¹ **Neutrino physics**

⁵²

The neutrino, or ν for the close friends, a fascinating and invisible particle. Some will say that dark matter also have those property but at least we are pretty confident that neutrinos exists.

⁵³ **1.1 Standard model**

⁵⁴ **1.1.1 Limits of the standard model**

⁵⁵ **1.2 Historic of the neutrino**

⁵⁶ **First theories**

⁵⁷ **Discovery**

⁵⁸ **Milestones and anomalies**

⁵⁹ **1.3 Oscillation**

⁶⁰ **1.3.1 Phenomologies**

⁶¹ **1.4 Open questions**

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⁶² **Chapter 2**

⁶³ **The JUNO experiment**

⁶⁴ “*Ave Juno, rosae rosam, et spiritus rex*”. It means nothing but I found it in tone.

⁶⁵ The first idea of a medium baseline (~ 52 km) experiment, was explored in 2008 [1] where it was
⁶⁶ demonstrated that the Neutrino Mass Ordering (NMO) could be determined by a medium baseline
⁶⁷ experiment if $\sin^2(2\theta_{13}) > 0.005$ without the requirements of accurate knowledge of the reactor
⁶⁸ antineutrino spectra and the value of Δm_{32}^2 . From this idea is born the Jiangmen Underground
⁶⁹ Neutrino Observatory (JUNO) experiment.

⁷⁰ JUNO is a neutrino detection experiment under construction located in China. Its main objectives
⁷¹ are the determination of the mass ordering at the $3\text{-}4\sigma$ level in 6 years of data taking and the mea-
⁷² surement at the sub-percent precision of the oscillation parameters Δm_{21}^2 , $\sin^2 \theta_{12}$, Δm_{32}^2 and with less
⁷³ precision $\sin^2 \theta_{13}$ [2].



FIGURE 2.1 – On the left: Location of the JUNO experiment and its reactor sources in southern china. On the right: Aerial view of the experimental site

⁷⁴ For this JUNO will measure the electronic anti-neutrinos ($\bar{\nu}_e$) flux coming from the nuclear reac-
⁷⁵ tors of Taishan, Yangjiang, for a total power of 26.6 GW_{th} , and the Daya Bay power plant to a lesser
⁷⁶ extent. Details about the power plants and there expected flux of $\bar{\nu}_e$ can be found in the table 2.1. The
⁷⁷ distance of 53 km has been specifically chosen to maximize the disappearance probability of the $\bar{\nu}_e$.

⁷⁸ **2.1 Neutrinos physics in JUNO**

⁷⁹ Even if JUNO design (section 2.2) was optimized for the measurement of the NMO, its large
⁸⁰ detection volume, excellent energy resolution and background level and understanding make it also
⁸¹ an excellent detector to measure the flux coming from other neutrino sources. Thus the scientific
⁸² program of JUNO extends way over reactor antineutrinos. The following section is an overview of
⁸³ the different physics topic JUNO will contribute in the coming years.

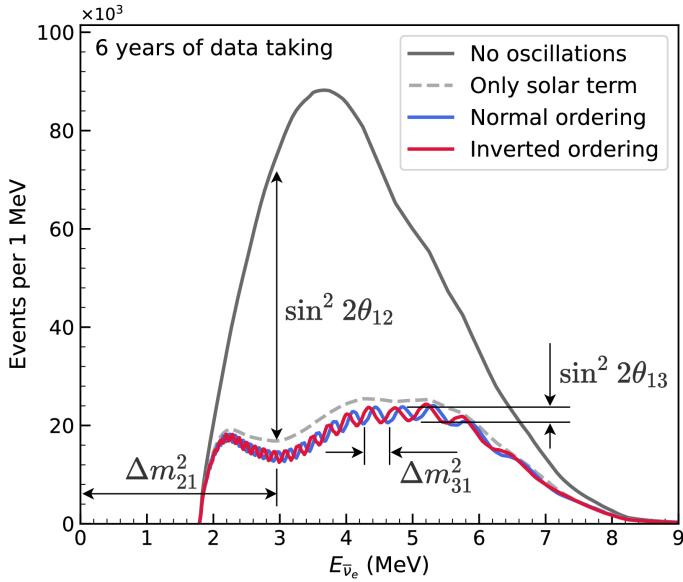


FIGURE 2.2 – Expected number of neutrinos event per MeV in JUNO after 6 years of data taking. The black curve shows the flux if there was no oscillation. The light gray curve shows the oscillation if only the solar terms are taken in account (θ_{12} , Δm_{21}^2). The blue and red curve shows the spectrum in the case of, respectively, NO and IO. The dependency of the oscillation to the different parameters are schematized by the double sided arrows. We can see the NMO sensitivity by looking at the fine phase shift between the red and the blue curve.

2.1.1 Reactor neutrino oscillation for NMO and precise measurements

Previous works [1, 3] shows that oscillation parameters and the NMO can be observed by looking at the $\bar{\nu}_e$ disappearance spectrum coming from medium baseline nuclear reactor. This disappearance probability can be expressed as [2] :

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

Where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$, E is the $\bar{\nu}_e$ energy and L is the baseline. We can see the sensitivity to the NMO in the dependency to Δm_{32}^2 and Δm_{31}^2 causing a phase shift of the spectrum as we can see in the figure 2.2. By carefully fitting this spectrum, one can extract the NMO and the oscillation parameters. The fit is reviewed in more details in the section 2.6.1. To reach the desired sensitivity, JUNO must meet multiple requirements but most notably:

1. An energy resolution of $3\%/\sqrt{E(\text{MeV})}$ to be able to distinguish the fine structure of the fast oscillation.
2. An energy precision of 1% in order to not err on the location of the oscillation pattern.
3. A baseline of 53 ± 0.5 km to maximise the $\bar{\nu}_e$ oscillation probability.
4. At least $\approx 100,000$ events to limit the spectrum distortion due to statistical uncertainties.

2.1.2 $\bar{\nu}_e$ flux coming from nuclear power plants

To get such high measurements precision, it is necessary to have a very good understanding of the sources characteristics. For its NMO and precise measurement studies, JUNO will observe the

98 energy spectrum of neutrinos coming from the nuclear power plants Taishan and Yangjiang's cores,
 99 located at 53 km of the detector to maximise the disappearance probability of the $\bar{\nu}_e$.

Reactor	Power (GW _{th})	Baseline (km)	IBD Rate (day ⁻¹)	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

TABLE 2.1 – Characteristics of the nuclear power plants observed by JUNO. The IBD rate are estimated from the baselines, the reactors full thermal power, selection efficiency and the current knowledge of the oscillation parameters

100 The $\bar{\nu}_e$ coming from reactors are emitted from β -decay of unstable fission fragments. The Taishan
 101 and Yangjiang reactors are pressurised water reactor (PWR), the same type as Daya Bay. In those
 102 type of reactor more the 99.7 % and $\bar{\nu}_e$ are produced by the fissions of four fuel isotopes ²³⁵U, ²³⁸U,
 103 ²³⁹Pu and ²⁴¹Pu. The neutrino flux per fission of each isotope is determined by the inversion of the
 104 measured β spectra of fission product [4–8] or by calculation using the nuclear databases [9, 10]. The
 105 neutrino flux coming from a reactor at a time t can be predicted using

$$\phi(E_\nu, t)_r = \frac{W_{th}(t)}{\sum_i f_i(t) e_i} \sum_i f_i(t) S_i(E_\nu) \quad (2.1)$$

106 where $W_{th}(t)$ is the thermal power of the reactor, $f_i(t)$ is the fraction fission of the i th isotope, e_i its
 107 thermal energy released in each fission and $S_i(E_\nu)$ the neutrino flux per fission for this isotope. Using
 108 this method, the flux uncertainty is expected to be of an order of 2-3 % [11].

109 In addition to those prediction, a satellite experiment named TAO[12] will be setup near the
 110 reactor core Taishan-1 to measure with an energy resolution of 2% at 1 MeV the neutrino flux coming
 111 from the core. It will help identifying unknown fine structure and give more insight on the $\bar{\nu}_e$ flux
 112 coming from this reactor.

113 One the open issue about reactor anti-neutrinos flux is the so-called neutrino anomaly [13], an
 114 unexpected surplus of neutrino emission in the spectra around 5 MeV. Multiples scientists are trying
 115 to explain this surplus by advanced recalculation of the nuclei model during beta decay [14, 15] but
 116 no consensus on this issue has been reached yet.

117 Background in the neutrinos reactor spectrum

118 Considering the close reactor neutrinos flux as the main signal, the signals that are considered as
 119 background are:

- 120 — The geoneutrinos producing background in the 0.511 ~ 2.7 MeV region.
- 121 — The neutrinos coming from the other nuclear reactors around Earth.

122 In addition to all those physics signal, non-neutrinos signal that would mimic an IBD will also be
 123 present. It is composed of:

- 124 — The signal coming from radioactive decay (α , γ , β) from natural radioactive isotopes in the
 material of the detector.
- 125 — Cosmogenic event such as fast neutrons and activated isotopes induced by muons passing
 through the detector, most notably the spallation on ¹²C.

¹²⁸ All those events represent a non-negligable part of the spectrum as shown in figure 2.3.

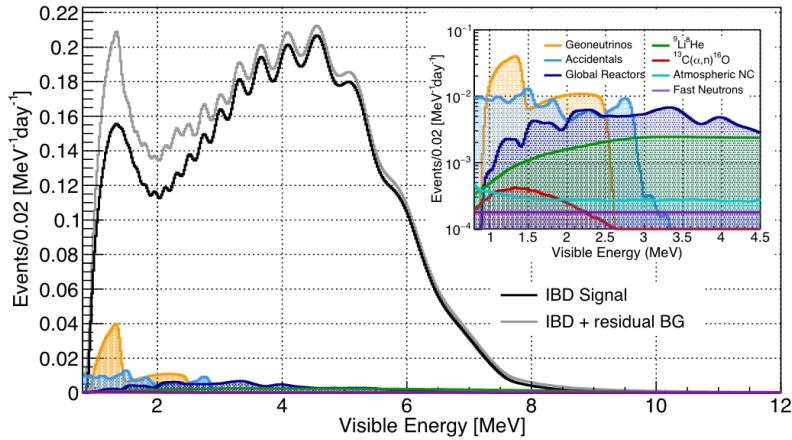


FIGURE 2.3 – Expected visible energy spectrum measured with the LPMT system with (grey) and without (black) backgrounds. The background amount for about 7% of the IBD candidate and are mostly localized below 3 MeV [11]

¹²⁹ Identification of the mass ordering

¹³⁰ To identify the mass ordering, we fit the neutrino energy spectrum under the two hypothesis of
¹³¹ NO and IO. Those two fit give us two χ^2 , respectively χ^2_{NO} and χ^2_{IO} . By computing the difference
¹³² $\Delta\chi^2 = \chi^2_{NO} - \chi^2_{IO}$ we can determine the most probable mass ordering: NO if $\Delta\chi^2 > 0$ and IO
¹³³ if $\Delta\chi^2 < 0$. Current studies shows that the expected sensitivity the mass ordering would be of
¹³⁴ 3.4σ after 6 years of data taking in nominal setup[2]. More detailed explanations about the fitting
¹³⁵ procedure can be found in the section 2.6.1.

¹³⁶ Precise measurement of the oscillations parameters

¹³⁷ The oscillations parameters θ_{12} , θ_{13} , Δm_{21}^2 , Δm_{31}^2 are free parameters in the fit of the oscillation
¹³⁸ spectrum. The precision on those parameters have been estimated and are shown in table 2.2. Wee
¹³⁹ see that for θ_{12} , Δm_{21}^2 , Δm_{31}^2 , precision at 6 years is better than the reference precision by an order of
¹⁴⁰ magnitude [11]

	Central Value	PDG 2020	100 days	6 years	20 years
$\Delta m_{31}^2 (\times 10^{-3} \text{ eV}^2)$	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
$\Delta m_{21}^2 (\times 10^{-3} \text{ eV}^2)$	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2 \theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2 \theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

TABLE 2.2 – A summary of precision levels fir the oscillation parameters. The reference value (PDG 2020 [16]) is compared with 100 days, 6 years and 20 years of JUNO data taking.

¹⁴¹ 2.1.2 Other physics

¹⁴² While the design of JUNO is tailored to measure $\bar{\nu}_e$ coming from nuclear reactor, JUNO will be
¹⁴³ able to detect neutrinos coming from other sources thus allowing for a wide range of physics studies
¹⁴⁴ as detailed in the table 2.3 and in the following sub-sections.

Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc	0–80 MeV	Negligible
DSNB (w/o PSD)	2300 elastic scattering		
Solar neutrino	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Atmospheric neutrino	hundreds per year for ${}^8\text{B}$	0–16 MeV	Radioactivity
Geoneutrino	hundreds per year	0.1–100 GeV	Negligible
	≈ 400 per year	0–3 MeV	Reactor ν

TABLE 2.3 – Detectable neutrino signal in JUNO and the expected signal rates and major background sources

145 **Geoneutrinos**

146 Geoneutrinos designate the antineutrinos coming from the decay of long-lived radioactive
 147 elements inside the Earth. The 1.8 MeV threshold necessary for the IBD makes it possible to measure
 148 geoneutrinos from ${}^{238}\text{U}$ and ${}^{232}\text{Th}$ decay chains. The studies of geoneutrinos can help refine the Earth
 149 crust models but is also necessary to characterise their signal, as they are a background to the mass
 150 ordering and oscillations parameters studies.

151 **Atmospheric neutrinos**

152 Atmospheric neutrinos are neutrinos originating from the decay of π and K particles that are
 153 produced in extensive air showers initiated by the interactions of cosmic rays with the Earth atmos-
 154 phere. Earth is mostly transparent to neutrinos below the PeV energy, thus JUNO will be able to
 155 see neutrinos coming from all directions. Their baseline range is large (15km \sim 13000km), they can
 156 have energy between 0.1 GeV and 10 TeV and will contain all neutrino and antineutrinos flavour.
 157 Their studies is complementary to the reactor antineutrinos and can help refine the constraints on
 158 the NMO [2].

159 **Supernovae burst neutrinos**

160 Neutrinos are crucial component during all stages of stellar collapse and explosion. Detection
 161 of neutrinos coming for core collapse supernovae will provide us important informations on the
 162 mechanisms at play in those events. Thanks to its 20 kt LS, JUNO has excellent capabilities to detect
 163 all flavour of the $\mathcal{O}(10 \text{ MeV})$ postshock neutrinos, and using neutrinos of the $\mathcal{O}(1 \text{ MeV})$ will give
 164 informations about the pre-supernovae neutrinos. All those informations will allow to disentangle
 165 between the multiple hydro-dynamic models that are currently used to describe the different stage
 166 of core-collapse supernovae.

167 **Diffuse supernovae neutrinos background**

168 Core-collapse supernovae in our galaxy are rare events, but they frequently occur throughout the
 169 visible Universe sending burst of neutrinos in direction of the Earth. All those events contributes to
 170 a low background flux of low-energy neutrinos called the Diffuse Supernovae Neutrino Background
 171 (DSNB). Its flux and spectrum contains informations about the red-shift dependent supernovae rate,
 172 the average supernovae neutrino energy and the fraction of black-hole formation in core-collapse su-
 173 pernovae. Depending of the DSNB model, we can expect 2-4 IBD events per year in the energy range
 174 above the reactor $\bar{\nu}_e$ signal, which is competitive with the current Super-Kamiokande+Gadolinium
 175 phase [17].

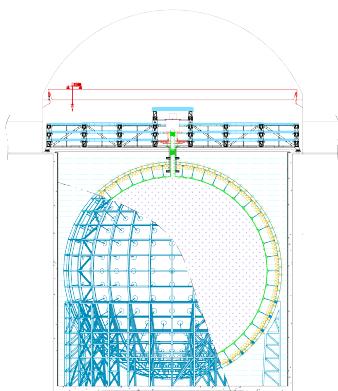
176 **Beyond standard model neutrinos interactions**

177 JUNO will also be able to probe for beyond standard model neutrinos interactions. After the
 178 main physics topics have been accomplished, JUNO could be upgraded to probe for neutrinoless
 179 beta decay ($0\nu\beta\beta$). The detection of such event would give critical informations about the nature
 180 of neutrinos, is it a majorana or a dirac particle. JUNO will also be able to probe for neutrinos that
 181 would come for the decay or annihilation of Dark Matter inside the sun and neutrinos from putative
 182 primordial black hole. Through the unitary test of the mixing matrix, JUNO will be able to search
 183 for light sterile neutrinos. Thanks to JUNO sensitivity, multiple other exotic can be performed on
 184 neutrino related beyond standard model interactions.

185 **2.2 The JUNO detector**

186 The JUNO detector is a scintillator detector buried 693.35 meters under the ground (1800 meters
 187 water equivalent). It consist of Central Detector (CD), a water pool and a Top Tracker (TT) as showed
 188 in figure 2.4a The CD is an acrylic vessel containing the 20 ktons of LS. It is supported by a stainless
 189 steel structure and is immersed in that water pool that is used as shielding from external radiation
 190 and as a cherenkov detector for the background. The top of the experiment is partially covered by
 191 the TT, a plastic scintillator detector which is use to detect the atmospheric muons background acting
 192 as veto detector.

193 The top of the experiment also host the LS purification system, a water purification system, a
 194 ventilation system to get rid of the potential radon in the air. The CD is observed by two system of
 195 Photo-Multipliers Tubes (PMT). They are attached to the steel structure and their electronic readout
 196 is submersed near them. A third system of PMT is also installed on the structure but are facing
 197 outward of the CD, instrumenting the water to be cherenkov detector. The CD and the cherenkov
 198 detector are optically separated by Tyvek sheet. A chimney for LS filling and purification and for
 199 calibration operations connects the CD to the experimental hall from the top.



(A) Schematics view of the JUNO detector.



(B) Top down view of the JUNO detector under construction

200 This section cover in details the different components of the detector and the detection systems.

201 **2.2.1 Principle of detection**

The CD will detect the neutrino and measure their energy mainly via an Inverse Beta Decay (IBD) interaction with proton (mainly ^{12}C and H) in the LS:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Kinematics calculation shows that this interaction has an energy threshold for the $\bar{\nu}_e$ of $(m_n + m_e - m_p) \approx 1.806$ MeV [18] where m_λ is the mass of the λ particle. This threshold make the experiment blind to very low energy neutrinos. The residual energy $E_\nu - 1.806$ MeV is be distributed as kinetic energy between the positron and the neutron. The energy of the emitted positron E_e is given by [18]

$$E_e = \frac{(E_\nu - \delta)(1 + \epsilon_\nu) + \epsilon_\nu \cos \theta \sqrt{(E_\nu - \delta)^2 + \kappa m_e^2}}{\kappa} \quad (2.2)$$

where $\kappa = (1 + \epsilon_\nu)^2 - \epsilon_\nu^2 \cos^2 \theta \approx 1$, $\epsilon_\nu = \frac{E_\nu}{m_p} \ll 1$ and $\delta = \frac{m_n^2 - m_p^2 - m_e^2}{2m_p} \ll 1$. We can see from this equation that the positron energy is strongly correlated to the neutrino energy.

The positron and the neutron will then propagate in the detection medium, the Liquid Scintillator (LS), loosing their kinetic energy by exciting the molecule of the LS (more details in section 2.2.2). Once stopped, the positron will annihilate with an electron from the medium producing two 511 KeV gamma. Those gamma will themselves interact with the LS, exciting it before being absorbed by photoelectrical effect. The neutron will be captured by an hydrogen, emitting a 2.2 MeV gamma in the process. This gamma will also deposit its energy before being absorbed by the LS.

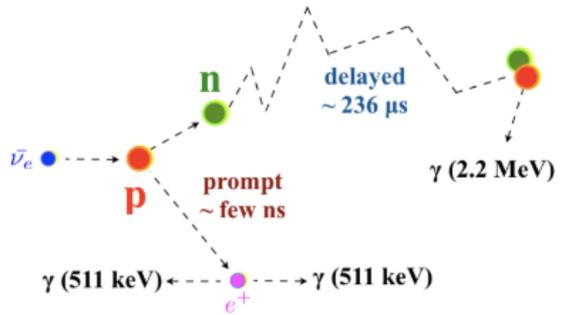


FIGURE 2.5 – Schematics of an IBD interaction in the central detector of JUNO

The scintillation photons have an UV frequency and will be captured by PMTs observing the CD. The analog signal of the PMTs digitized by the electronic is the signal of our experiment. The signal produced by the positron is subsequently called the prompt signal, and the signal coming from the neutron the delayed signal. This naming convention come from the fact that the positron will deposit its energy rather quickly (few ns) where the neutron will take a bit more time (~ 236 μ s).

2.2.2 Central Detector (CD)

The central detector, composed of 20 ktons of Liquid Scintillator (LS), is the main part of JUNO. The LS is contained in a spherical acrylic vessel supported by a stainless steel structure. The CD and its structural support are submerged in a cylindrical water pool of 43.5m diameter and 44m height. We're confident that the water pool provide sufficient buffer protection in every direction against the rock radioactivity.

Acrylic vessel

The acrylic vessel is a spherical vessel of inner diameter of 35.4 m and a thickness of 120 mm. It is assembled from 265 acrylic panels, thermo bonded together. The acrylic recipes has been carefully tuned with extensive R&D to ensure it does not include plasticizer and anti-UV material that would stop the scintillation photons. Those panels requires to be pure of radioactive materials to not cause background. Current setup where the acrylic panels are molded in cleanrooms of class 10000, let us reach a uranium and thorium contamination of <0.5 ppt. The molding and thermoforming processes is optimized to increase the assemblage transparency in water to >96%. The acrylic vessel

is supported by a stainless steel structure via supporting node (fig 2.6). The structure and the nodes are designed to be resilient to natural catastrophic events such as earthquake and can support many times the effective load of the acrylic vessel.

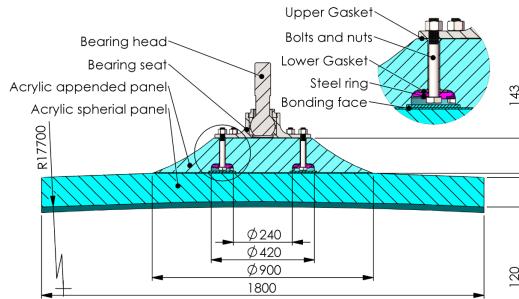


FIGURE 2.6 – Schematics of the supporting node for the acrylic vessel

236 Liquid scintillator

237 The Liquid Scintillator (LS) has a similar recipe as the one used in Daya Bay [19] but without
 238 gadolinium doping. It is made of three components, necessary to shift the wavelength of emitted
 239 photons to prevent their reabsorption:

- 240 1. The detection medium, the *linear alkylbenzene* (LAB). Selected because of its excellent trans-
 241 parency, high flash point, low chemical reactivity and good light yield. Accounting for \sim
 242 98% of the LS, it is the main component with which ionizing particles and gamma interact.
 243 Charged particles will collide with its electronic cloud transferring energy to the molecules,
 244 gamma will interact via compton effect with the electronic cloud before finally be absorbed
 245 via photoelectric effect.
- 246 2. The second component of the LS is the *2,5-diphenyloxazole* (PPO). A fraction of the excitation
 247 energy of the LAB is transferred to the PPO, mainly via non radiative process [20]. The
 248 PPO molecules de-excites in the same way, transferring their energy to the bis-MSB. The PPO
 249 makes for 1.5 % of the LS.
- 250 3. The last component is the *p-bis(o-methylstyryl)-benzene* (bis-MSB). Once excited by the PPO, it
 251 will emit photon with an average wavelength of \sim 430 nm (full spectrum in figure 2.7) that
 252 can be detected by our photo-multipliers systems. It amount for \sim 0.5% of the LS.

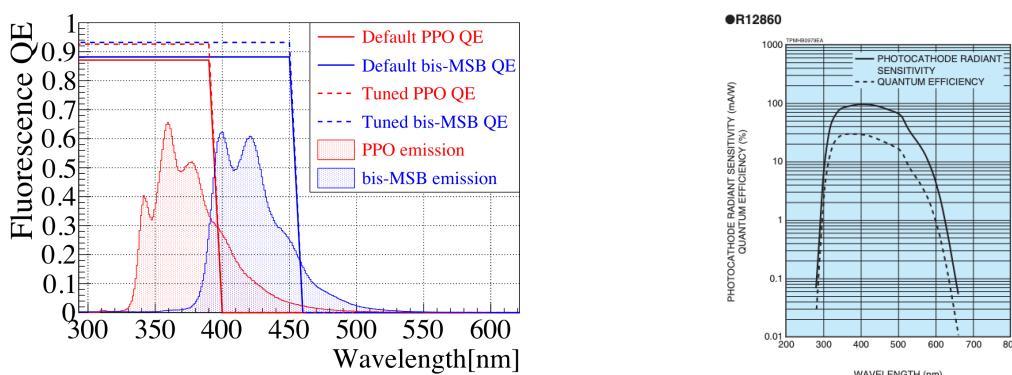


FIGURE 2.7 – On the left: Quantum efficiency (QE) and emission spectrum of the LAB and the bis-MSB [19]. On the right: Sensitivity of the Hamamatsu LPMT depending on the wavelength of the incident photons [21].

This formula has been optimized using dedicated studies with a Daya Bay detector [19, 22] to reach the requirements for the JUNO experiment:

- A light yield / MeV of the amount of 10^4 photons to maximize the statistic in the energy measurement.
- An attenuation length comparable to the size of the detector to prevent losing photons during their propagation in the LS. The final attenuation length is 25.8m [23] to compare with the CD diameter of 35.4m.
- Uranium/Thorium radiopurity to prevent background signal. The reactor neutrino program require a contamination fraction $F < 10^{-15}$ while the solar neutrino program require $F < 10^{-17}$.

The LS will frequently be purified and tested in the Online Scintillator Internal Radioactivity Investigation System (OSIRIS) [24] to ensure that the requirements are kept during the lifetime of the experiment.

Large Photo-Multipliers Tubes(LPMTs)

The scintillation light produced by the LS is then collected by Photo-Multipliers Tubes (PMT) that transform the incoming photon into an electric signal. As described in figure 2.8, the incident photons interact with the photocathode via photoelectric effect producing an electron called a Photo-Electron (PE). This PE is then focused on the dynodes where the high voltage will allow it to be multiplied. After multiple amplification, the electrons are read by the anode producing an electric signal that will need to be digitalized by the readout electronics.

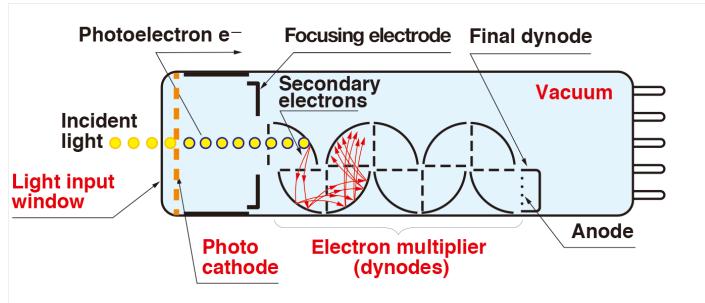


FIGURE 2.8 – Schematic of a PMT

The Large Photo-Multipliers Tubes (LPMT), used in the central detector and in the water pool, are 20-inch (50.8 cm) radius PMTs. ~ 5000 dynode-PMTs [21] were produced by the Hamamatsu[®] company and ~ 15000 Micro-Channel Plate (MCP) [25] by the NNVT[®] company. This system is the one responsible for the energy measurement with a energy resolution of $3\%/\sqrt{E}$, resolution necessary for the mass ordering measurement. To reach this precision, the system is composed of 17612 PMTs quasi uniformly distributed over the detector for a coverage of 75.2% reaching ~ 1800 PE/MeV or $\sim 2.3\%$ resolution due to statistic, leaving $\sim 0.7\%$ for the systematic uncertainties. To maintain the resolution over the lifetime of the experiment, JUNO require a failure rate $< 1\%$ over 6 years.

The LPMTs electronic are divided in two parts. One "near", located underwater, in proximity of the LPMT to reduce the cable length between the PMT and early electronic. A second one, outside of the detector that is responsible for higher level analysis before sending the data to the DAQ.

The light yield per MeV induce that a LPMT can collect between 1 and 1000 PE per event, causing non linearity in the PMT response that need to be understood and calibrated.

TODO: Relate

Small Photo-Multipliers Tubes (SPMTs)

The Small PMT (SPMTs), on the other hand, are 3-inch (7.62 cm) PMTs. They will be used in the CD as a secondary detection system. Those 25600 SPMTs will observe the same events as the LPMTs,

thus sharing the physics and detector systematics up until the photon conversion. With a detector coverage of 2.7%, this system will collect ~ 43 PE/MeV for a final energy resolution of $\sim 17\%$. This resolution is not enough to measure the MO, θ_{13} , Δm_{31}^2 but will be sufficient to independently measure θ_{12} and Δm_{21}^2 .

Due to the low PE rate, SPMTs will be running in photo-counting mode in the reactor range thus will be insensitive to non-linearity effect. Also, due to their smaller size and electronics, SPMTs have a better timing resolutions than the LPMTs. At higher energy range, like supernovae events, LPMTs will saturate where SPMTs due to their lower PE collection will be able do give measurement of the energy spectrum.

The Data Acquisition System (DAQ) is designed to support the event rate of IBD, background, dark noise and supplementary storage buffers are present in the LPMT electronics to withstand the event rate during supernovae burst.

2.2.3 Veto detector

The CD will be bathed in constant background noise coming from numerous, the radioactivity from surrounding rock, the radioactivity of its own components or from the cosmic muons. This background needs to be rejected to ensure the purity of the IBD spectrum. To prevent a big part of them, JUNO use two veto detector that will tag events as background before CD analysis.

Cherenkov in water pool

The Water Cherenkov Detector (WCD) is the instrumentalization of the water buffer around the CD. When high speed charged particles will pass through the water, they will produced cherenkov photons. The light will be collected by 2400 MCP LPMTs installed on the outer surface of the CD structure. The muons veto strategy is based on a PMT multiplicity condition. WCD PMTs are grouped in ten zones: 5 in the top, 5 in the bottom. Veto are raised either when more than 19 PMTs are triggered in one zone or when two adjacent zones simultaneously trigger more than 13 PMTs. Using this trigger, we expect to reach a muon detection efficiency of 99.5% while keeping the noise at reasonable level.

Top tracker

The JUNO Top Tracker (TT) is a plastic scintillator detector located on the top of the experiment (see figure 2.9). Made from plastic scintillator from OPERA [26] layered horizontally in 3 layers on the top of the detector, the TT will be able to detect incoming atmospheric muons. With its coverage, about 1/3 of the of all atmospheric muons that passing through the CD will also pass through the 3 layer of the detector. While it does not cover the majority of the detector, the TT is particularly effective to detect muons coming through the filling chimney region which might present difficulties from the other subsystems in some classes of events.

2.3 Calibration strategy

The calibration is a crucial part of the JUNO experiment. Because we are looking at civil reactor neutrino it might be impossible to run measurement without signal, it would need to shut down every reactor from the Taishan and Yangjiang power plants which is realistically impossible. Because of this continuous rate, low frequency signal event, we need high frequency, recognisable sources in the energy range of interest, [0-12] MeV for the positron signal and 2.2 MeV for the neutron capture. It is understood that the CD response will be different depending on the type of particle and on the position on the event due to the absorption length of the LS and the optical response of the acrylic sphere (see section 2.5). The energy response is also expected to be non-linear due to the LS response [19] but also due to the saturation of the LPMTs system when collecting a large amount of PE [27].

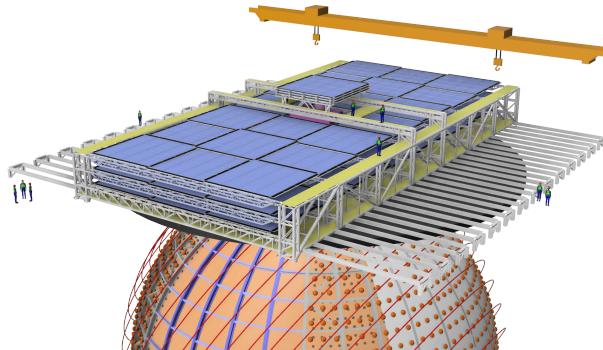


FIGURE 2.9 – The JUNO top tracker

2.3.1 Energy scale calibration

While electrons and positrons sources would be ideal, for a large LS detector, thin-walled electrons or positrons sources could lead to leakage of radionuclides causing contamination. Instead are considered gamma sources in the range of the prompt energy of IBDs. The sources are reported in table 2.4.

Sources / Processes	Type	Radiation
^{137}Cs	γ	0.0662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
$^{241}\text{Am-Be}$	n, γ	neutron + 4.43 MeV ($^{12}\text{C}^*$)
$^{241}\text{Am-}^{13}\text{C}$	n, γ	neutron + 6.13 MeV ($^{16}\text{O}^*$)
$(n, \gamma)p$	γ	2.22 MeV
$(n, \gamma)^{12}\text{C}$	γ	4.94 MeV or 3.68 + 1.26 MeV

TABLE 2.4 – List of sources and their process considered for the energy scale calibration

For the ^{68}Ge source, it'll decay in ^{68}Ga via electron capture, which will itself β^+ decay into ^{68}Zn . The positrons will be absorbed by the enclosure so only the annihilation gamma will be released. In addition, (α, n) sources like $^{241}\text{Am-Be}$ and $^{241}\text{Am-}^{13}\text{C}$ are used to provide both high energy gamma and neutrons, which will later be captured in the LS producing the 2.2 MeV gamma.

From this calibration we call E_{vis} the "visible energy" that is reconstructed by our current algorithms and we compare it to the true energy deposited by the calibration source. The results shown in figure 2.10 show the expected response of the detector from calibration sources. The non-linearity is clearly visible from the $E_{\text{vis}}/E_{\text{true}}$ shape. See [28] for more details.

2.3.2 Calibration system

The JUNO detector will need to investigate the non-uniformity in the detector response, more explication can be found in section 2.5. For this we can deploy sources using multiples systems that are schematized in figure 2.11 :

- For a one-dimension vertical calculation, the Automatic Calibration Unit (ACU) will be able to deploy multiple radioactive sources or a pulse laser diffuser ball along the central axis of the CD through the top chimney. The source position precision is less than 1cm.

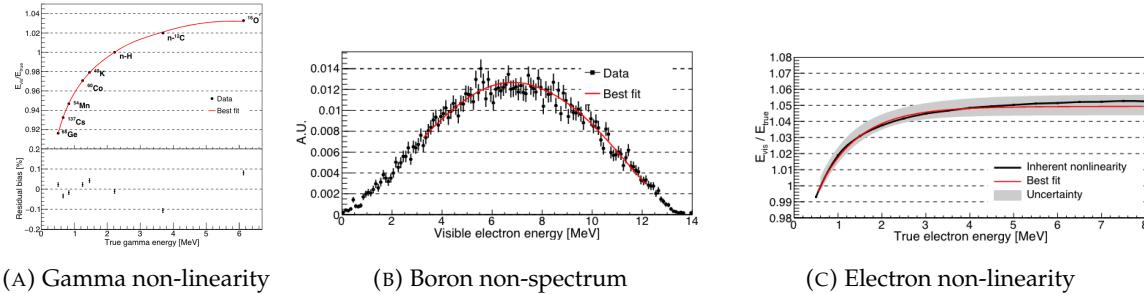


FIGURE 2.10 – Fitted and simulated non linearity of gamma and electron sources and ^{12}B spectrum. Black points are simulated data while red points are the best fit

- For off-axis calibration, a calibration source attached to a Cable Loop System (CLS) can be moved on a vertical half-plane by adjusting the length of two connection cable. Two set of CSL will be deployed to provide a 79% effective coverage of a vertical plane.
- A Guiding Tube (GT) will surround the CD to calibrate the non-uniformity of the response at the edge of the detector
- A Remotely Operated under-LS Vehicle (ROV) can be deployed to desired location inside LS for a more precise and comprehensive calibration. The ROV will also be equipped with a camera for inspection of the CD.

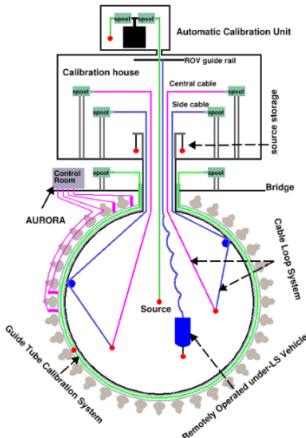


FIGURE 2.11 – Overview of the calibration system

- The preliminary calibration program is depicted in table 2.5.

2.4 Software

The simulation, reconstruction and analysis algorithms are all packaged in the JUNO software, subsequently called the software. It is composed of multiple components integrated in the SNiPER [29] framework:

- Various primary particles simulators for the different kind of events, background and calibration sources.
- A Geant4 [30–32] simulation simulating the detectors geometries, a custom optical model for the LS and the supporting structures of the detectors. The Geant4 simulation integrate all relevant physics process for JUNO, validated by the collaboration. This step of the simulation is commonly called *Detsim* and compute up to the production of photo-electrons in the PMTs.

Program	Purpose	System	Duration [min]
Weekly calibration	Neutron (Am-C)	ACU	63
	Laser	ACU	78
Monthly calibration	Neutron (Am-C)	ACU	120
	Laser	ACU	147
	Neutron (Am-C)	CLS	333
	Neutron (Am-C)	GT	73
Comprehensive calibration	Neutron (Am-C)	ACU, CLS and GT	1942
	Neutron (Am-Be)	ACU	75
	Laser	ACU	391
	⁶⁸ Ge	ACU	75
	¹³⁷ Cs	ACU	75
	⁵⁴ Mn	ACU	75
	⁶⁰ Co	ACU	75
	⁴⁰ K	ACU	158

TABLE 2.5 – Calibration program of the JUNO experiment

- 373 The optics properties of the different materials and detector components have been measured
 374 beforehand to be used to define the material and surfaces in the simulation
 375 — An electronic simulation, simulating the response waveform of the PMTs, tracking it through
 376 the digitization process, accounting for effects such as non-linearity, dark noise, Time Transit
 377 Spread (TTS), pre-pulsing, after-pulsing and ringing of the waveform. This step is commonly
 378 referenced as *ElecSim*.
 379 — A waveform reconstruction where the digitized waveform are filtered to remove high-frequency
 380 white noise and then deconvoluted to yield time and charge informations of the photons hits
 381 on the PMTs. This step is commonly referenced as *Calib*.
 382 — The charge and time informations are used by reconstruction algorithms to reconstruct the
 383 interaction vertex and the deposited energy. See section 2.5 for more details on the reconstruc-
 384 tion.
 385 — Once the singular events are reconstructed, they go through event pairing and classification
 386 to select IBD events.

387 2.5 State of the art of the IBD reconstruction in JUNO

388 The main reconstruction method currently run in JUNO is a data-driven method based on a
 389 likelihood maximization [33, 34]. The first step is to reconstruct the interaction vertex from which
 390 the energy reconstruction is dependent. It is also necessary for event pairing and classification.

391 2.5.1 Interaction vertex reconstruction

392 To start the likelihood maximization, a rough estimation of the vertex is made using a charge-
 393 based algorithm and a time based algorithm.

394 Charge based algorithm

395 The charge-based algorithm is basically base on the charge-weighted average of the PMT position.

$$\vec{r}_{cb} = a \cdot \frac{\sum_i q_i \cdot \vec{r}_i}{\sum_i q_i} \quad (2.3)$$

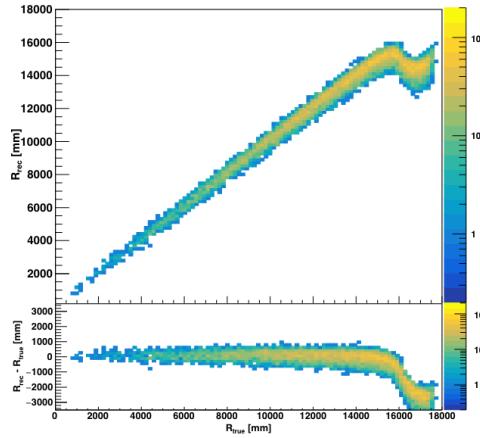


FIGURE 2.12 – Heatmap of R_{rec} and $R_{rec} - R_{true}$ as a function of R_{true} for 4MeV prompt signals uniformly distributed in the detector

396 Where q_i is the reconstructed charge of the pulse of the i th PMT and \vec{r}_i is its position. \vec{r}_0 is the
 397 reconstructed interaction position. a is a scale factor introduced because a weighted average over a
 398 3D sphere is inherently biased. Using calibration we can estimate $a \approx 1.3$ [35]. The results in figure ??
 399 shows that the reconstruction is biased from around 15m and further. This is due to the phenomena
 400 called “total reflection area” or TR Area.

401 **2.5.2 Energy reconstruction**

402 **2.5.3 Particle identification**

403 **2.5.4 Machine learning for reconstruction**

404 **Vertex reconstruction**

405 **Energy reconstruction**

406 **2.6 JUNO sensitivity to NMO and precise measurements**

407 **2.6.1 Fitting procedure**

⁴⁰⁸ **Chapter 3**

⁴⁰⁹ **Machine learning and Artificial
Neural Network**

⁴¹¹ **3.1 History of the Machine learning**

⁴¹² **3.2 Boosted Decision Tree (BDT)**

⁴¹³ **3.3 Artificial Neural Network (NN)**

⁴¹⁴ **3.3.1 Fully Connected Deep Neural Network (FCDNN)**

⁴¹⁵ **3.3.2 Convolutional Neural Network (CNN)**

⁴¹⁶ **3.3.3 Graph Neural Network (GNN)**

⁴¹⁷ **3.3.4 Adversarial Neural Network (ANN)**

⁴¹⁸ **Generative Adversarial Network (GAN)**

⁴¹⁹ **Reinforcement Learning (RL)**

⁴²⁰ **Random Search (RS)**

⁴²¹ **Bayesian Optimization**

⁴²² **Chapter 4**

⁴²³ **Image recognition for IBD
reconstruction with the SPMT system**

⁴²⁴

⁴²⁵ **Chapter 5**

⁴²⁶ **Graph representation of JUNO for IBD
reconstruction with the LPMT system**

⁴²⁷

⁴²⁸ Chapter 6

⁴²⁹ **Reliability of machine learning
methods**

⁴³⁰

⁴³¹ **Chapter 7**

⁴³² **Discrimination of e+/e- events in
JUNO**

⁴³³

⁴³⁴ **Chapter 8**

⁴³⁵ **Conclusion**

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