DOCTORAT BRETAGNE LOIRE / MATIERE MOLECULES ET MATERIAUX

UNIVERSITÉ DE NANTES

THÈSE DE DOCTORAT DE

L'UNIVERSITÉ DE NANTES

ÉCOLE DOCTORALE N° 596
Matière, Molécules, Matériaux
Spécialité : *Physique des particules*

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

Thèse présentée et soutenue à Nantes, le Too soon and too early at the same time
Unité de recherche : Laboratoire SUBATECH, UMR 6457

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List of Abbreviations

NMO	**N**eutrino **M**ass **O**rdering
JUNO	**J**iangmen **U**nderground **N**eutrino **O**bservatory
NO	**N**ormal **O**rdering
IO	**I**nverse **O**rdering
IBD	**I**nverse **B**eta **D**ecay
LS	**L**iquid **S**cintillator

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Introduction

Chapter 1

Neutrino physics

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.

1.1 Standard model

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1.1.1 Limits of the standard model

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Chapter 2

The JUNO experiment

"Ave Juno, rosae rosam, et spiritus rex". It means nothing but I found it in tone.

The first idea of a medium baseline (60 km) experiment, was explored in 2008 where it was demonstrated that the Neutrino Mass Ordering (NMO) could be determined by a medium baseline experiment if $\sin^2(2\theta_{13}) > 0.005$ without requirements on accurate information of the reactor antineutrino spectra and the value of Δm^2_{32}. [1]. From this idea is born the Jiangmen Underground Neutrino Observatory (JUNO) experiment.

JUNO is a neutrino detection experiment under construction located in China. Its main objectives are the determination of the mass ordering at the 3-4σ level in 6 years of data taking and the measurement at the per-mil precision of the oscillation parameters Δm^2_{21}, $\sin^2 2\theta_{12}$, Δm^2_{32} and, with less 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:** external view of the experimental site

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

2.1 Neutrinos physics in JUNO

2.1.1 $\bar{\nu}_e$ flux coming from nuclear power plants

To get such high measurements precision, it is necessary to have a very good understanding of the source characteristics. For its main studies, JUNO will measure the energy of neutrinos coming from core of nuclear power plants of Taishan and Yangjiang, 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

The $\bar{\nu}_e$ coming from reactors are emitted from β-decay of unstable fission fragments. The Taishan and Yangjiang reactors are pressurised water reactor (PWR), the same type as Daya Bay. In those type of reactor more the 99.7 % and $\bar{\nu}_e$ are produced by the fissions of four fuel isotopes ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. The neutrino flux per fission of each isotope is determined by the inversion of the measured β spectra of fission product [3–7] or by calculation using the nuclear databases [8, 9]. The neutrino flux coming from a reactor at a time t can be predicted using

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

where $W_{th}(t)$ is the thermal power of the reactor, $f_i(t)$ is the fraction fission of the ith isotope, e_i its thermal energy released in each fission and $S_i(e_\nu)$ the neutrino flux per fission for this isotope. Using this method, the flux uncertainty is expected to be of an order of 2-3 % [10].

In addition to those prediction, a satellite experiment named TAO[11] will be setup the reactor core Taishan 1 to measure with an energy resolution of 2% at 1 MeV the neutrino

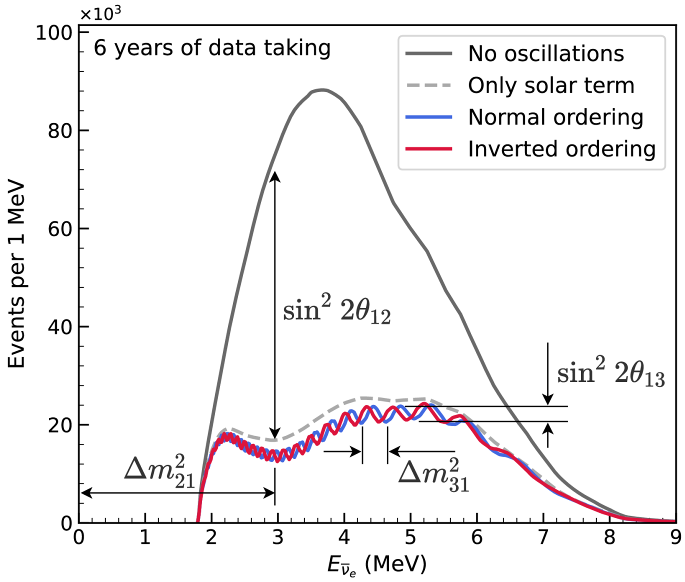

FIGURE 2.2 – Expected number of neutrinos event per MeV in JUNO after 6 years of data taking. The black curve shows the flux if there was no oscillation. The light gray curve shows the oscillation if only the solar terms are taken in account (θ_{12}, Δm^2_{21}). The blue and red curve shows the spectrum 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.

flux coming from the core to identify unknown fine structure and give more insight on the $\bar{\nu}_e$ flux coming from this reactor.

2.1.2 Reactor neutrino oscillation for NMO and precise measurements

Previous works [1, 12] 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] :

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

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^2_{32} and Δm^2_{31} 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 $3\%/\sqrt{E(\mathrm{MeV})}$ 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 dur to statistical uncertainties.

Identification of the mass ordering

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

Precise measurement of the oscillations parameters

The oscillations parameters θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31} are free parameters in the fit of the oscillation spectrum. The precision on those parameters have been estimated and are shown in figure 2.3. Wee see that for θ_{12}, Δm^2_{21}, Δm^2_{31}, precision at 6 years is better than the reference precision by an order of magnitude [10]

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

FIGURE 2.3 – A summary of precision levels fir the oscillation parameters. The reference value (PDG 2020 [13]) is compared with 100 days, 6 years and 20 years of JUNO data taking.

2.1.3 Other physics

While the design of JUNO is tailored to measure $\bar{\nu}_e$ coming from nuclear reactor, JUNO will be able to detect neutrinos coming from other sources thus allowing for a wide range of physics studies as detailed in the table 2.2 and in the following sub-section.

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
	2300 elastic scattering		
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	≈ 400 per year	0–3 MeV	Reactor ν

TABLE 2.2 – Detectable neutrino signal in JUNO and the expected signal rates and major background sources

Geoneutrinos

Geoneutrinos designate the antineutrinos coming from the decay of long-lived radioactive elements inside the Earth. The 1.8 MeV threshold necessary for the IBD makes it possible to measure geoneutrinos from ^{2}38U and ^{2}32Th decay chains. The studies of geoneutrinos can help refine the Earth crust models but is also necessary to characterise their signal, as they are a background to the mass ordering and oscillations parameters studies.

Atmospheric neutrinos

Atmospheric neutrinos are neutrinos originating from the decay of π and K particles that are produced in extensive air showers initiated by the interactions of cosmic rays with the Earth atmosphere. Earth is mostly transparent to neutrinos below the PeV energy, thus JUNO will be able to see neutrinos coming from all directions. Their baseline range is large (15km $\sim$ 13000km), they can have energy between 0.1 GeV and 10 TeV and will contain all neutrino and antineutrinos flavour. Their studies is complementary to the reactor antineutrinos and can bring constraint on the MO [2].

Beyond standard model neutrinos interactions

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

Supernovae burst neutrinos

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

Diffuse supernovae neutrinos background

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

Background in the neutrinos reactor spectrum

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

- The geoneutrinos producing background in the $0.511 \sim 2.7$ MeV region.
- The neutrinos coming from the other nuclear reactors around Earth.

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

- The signal coming from radioactive decay $(\alpha,\ \gamma,\ \beta)$ from natural radioactive isotopes in the material of the detector.
- Cosmogenic event such as fast neutrons and activated isotopes induced by muons passing through the detector, most notably the spallation on ^{1}2C.

All those events represent a non-negligeable part of the spectrum as shown in figure 2.4.

2.2 The JUNO detector

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2.2.1 Principle of detection

JUNO will be able to detect neutrinos and measure their energy mainly via the Inverse Beta Decay (IBD) interaction

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

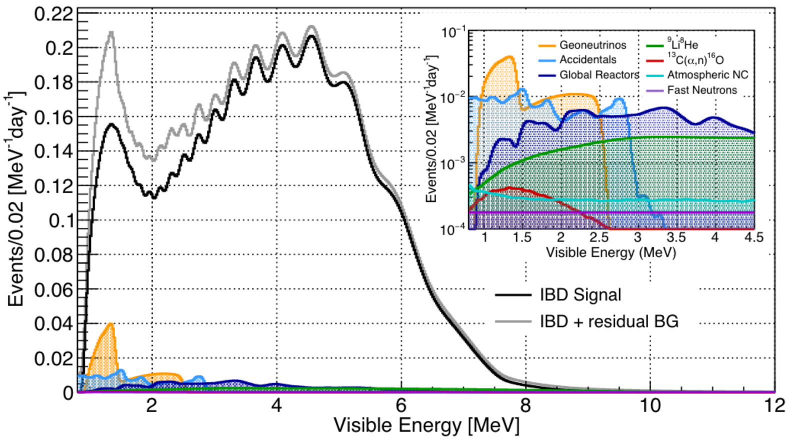

FIGURE 2.4 – Expected visible energy spectrum measured with the LPMT system with (grey) and without (black) backgrounds. The background amount for about 7% of the IBD candidate and are mostly localized below 3 MeV [10]

Simple kinematics calculation shows that the $\bar{\nu}_e$ must have an energy of $(m_n + m_e - m_p) \approx 1.806$ MeV [14] 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 [14]

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

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.

Once the positron and the neutron will propagate in the detection medium, the liquid scintillator (LS), loosing their kinetic energy by exciting with the LS. 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.

More details about the LS can be found in section 2.2.2.

The scintillation photons will then be captured by the photo-multipliers (PMTs) surrounding the experiment. The analogue signal, then 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 ($\sim 236\ \mu$s).

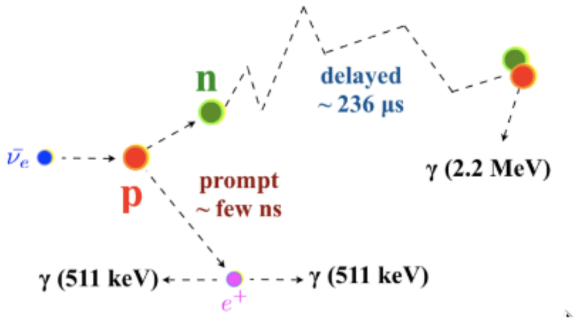

FIGURE 2.5 – Schematics of an IBD interaction in the central detector of JUNO

2.2.2 Central Detector (CD)

Acrylic containment sphere

Liquid scintillator

Large photo-multipliers (LPMTs)

Small photo-multipliers (SPMTs)

Data Acquisition System (DAQ)

Simulation

Software

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