Study of the sensitivity to measure ν oscillation parameters with JUNO

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The JUNO experiment aims to precisely determine key neutrino properties, such as the CP violation phase and Neutrino Mass Ordering (NMO). Our project began by modeling reactor neutrino flux and analyzing the detected anti-neutrino spectrum. Once implemented, it was possible to determine the anti-neutrinos spectrum detected from the different selection parameters of the detector. By conducting a chi-square analysis using estimated measurement uncertainties, we identified the optimal detector-to-reactor distance for discerning the neutrino mass hierarchy effectively.

INTRODUCTION

Two crucial parameters that remain poorly understood are the neutrino CP violation phase and the Neutrino Mass Ordering (NMO). The CP violation phase, characterizing differences in neutrino and antineutrino behavior, provides insights into fundamental asymmetries in the universe. Simultaneously, the Neutrino Mass Ordering (Figure 1), describing the mass hierarchy among different neutrino types, is key to understanding cosmic evolution and fundamental particle physics processes. Determining these parameters will enhance our understanding of the fundamental nature of neutrinos and allow for new advancements in particle physics and astrophysics.

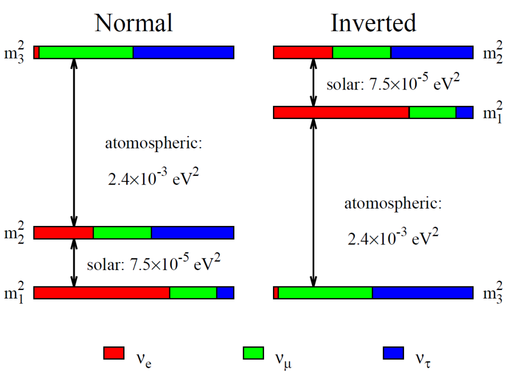

Figure 1. Illustration for the patterns of normal and inverted neutrino mass hierarchies [1]

The JUNO experiment represents a new opportunity to determine the neutrino mass hierarchy. Located in China, JUNO is a massive liquid scintillator detector, designed to capture electron antineutrinos emitted from nearby nuclear reactors. By analyzing the energy spectrum and interaction patterns of these antineutrinos, JUNO aims to discern the oscillations related to the neutrino mass hierarchy. With its unprecedented scale and sensitivity, JUNO could deliver precious insights into fundamental neutrino properties, including the mass hierarchy.

ANTINEUTRINOS FLUX

The JUNO experiment is located nearby two nuclear power plants, at a distant of 53 from each. The reactor fuel of those power plant is composed by four main isotopes ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu. The $\overline{\nu}_e$ flux from those isotopes can be implemented (Figure 2) using the antineutrinos energy by [3]:

$$\begin{aligned}\phi(E) = 0.58Exp&(0.870 - 0.160E - 0.091E^2)\\ &+ 0.30Exp(0.896 - 0.239E - 0.0981E^2)\\ &+ 0.07Exp(0.976 - 0.162E - 0.0790E^2)\\ &+ 0.05Exp(0.793 - 0.080E - 0.1085E^2)\end{aligned} \tag{1}$$

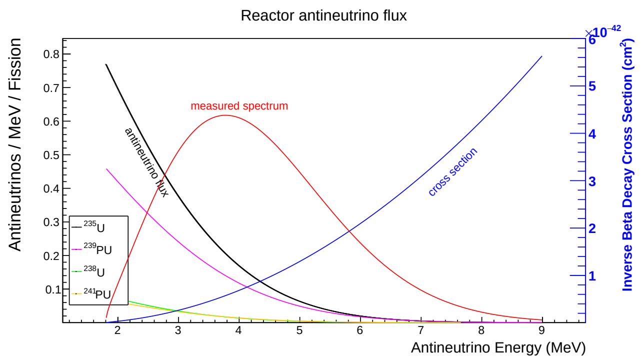

Figure 2. antineutrinos flux and IBD cross section

The observed neutrino spectrum can be express as [3] :

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(E) \tag{2}$$

where L is the distant between the reactor and detector, and $\sigma(E)$ is the inverse β decay ($\overline{\nu}_e + p \rightarrow e^+ + n$) cross section, which can be expressed using the positron energy [3] :

$$\sigma(E_e, p_e) = 0.095210^{-42}cm^2(E_e p_e/1MeV^2) \tag{3}$$

and $P_{ee}(E)$ is the surival propability of the $\overline{\nu}_e$:

$$\begin{aligned}P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32}\\ P21 &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})\\ P31 &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})\\ P32 &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})\end{aligned} \tag{4}$$

with $\Delta_{ij} = 1.27\Delta m_{ij}^2 L/E$ is the neutrinos mass-squared difference and θ_{ij} the mixing angle. The probability, and thus the spectrum depend of the mass hierarchy (Figure 3).

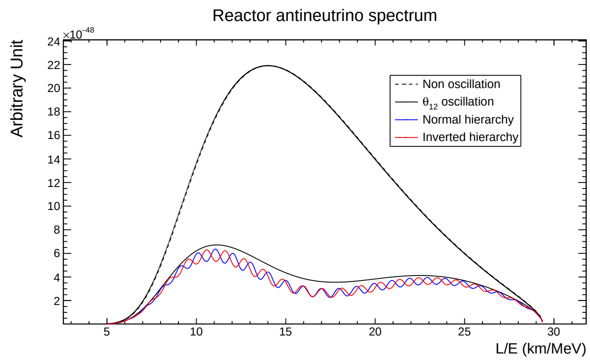

Figure 3. Antineutrinos spectrum as function of L/E

DETECTION SYSTEM

Because the resolution of the detector energy is not perfect, the oscillations of the antineutrinos flux will be affected. Indeed, the visible energy resolution of the detector can be implemented by a Gaussian function with a standard deviation given by [2]:

$$\frac{\sigma_{E_{\text{vis}}}}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2} \tag{5}$$

Because of this uncertainty, from the detected energy it wont be possible to perfectly reconstruct the flux. In this study $a = 3\%\sqrt{MeV}$, and $b = c = 0$ as the background is not considered. Using a convolution the reconstructed spectrum of the anti neutrinos can be determined from the visible energy by (Figure 4) :

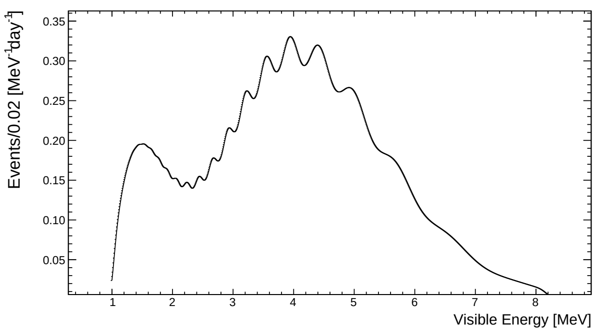

Figure 4. Antineutrinos events flux (IH) as function of E_{vis}

χ^2 ANALYSIS

To determine the sensitivity of the detector a chi-squared analysis can be perform using the Pearson model given by [1]:

$$\chi^2_{REA} = \sum_{i=1}^{N_{bin}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\epsilon_k]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2} \tag{6}$$

with M_i the mesured events, T_i the predicted ones, σ_k the systematic uncertainty, ϵ_l the pull parameter and α_{ik} the fraction of event contribution. In this project the systematic uncertainty has been ignored. Using a projection of the 6 years data of JUNO it is possible to determine the new uncertainties of the parameters at 1σ level considering a change by a unit in the χ^2 squared function.(Figure 5) Another interesting aspect of the χ^2 test is that it is

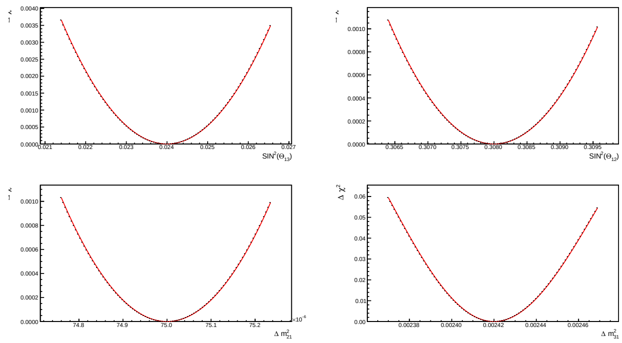

Figure 5. $\Delta\chi^2$ (not normalized) for different parameter variations (IH)

possible to determine the optimal distance value of the detector from the reactor to maximise the differentiation of the mass hierarchy [1]:

$$\Delta\chi^2_{MH} = |\chi^2_{min}(N) - \chi^2_{min}(I)| \tag{7}$$

The maximum is obtained at L=53km, which is indeed the actual position of the JUNO experiment (Figure 6).

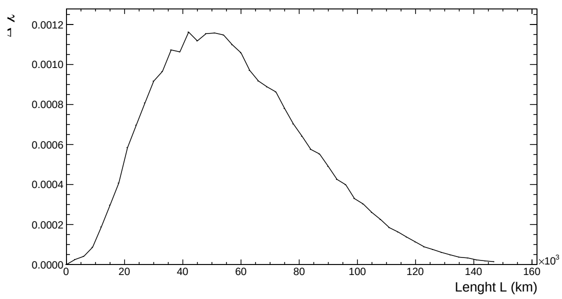

Figure 6. $\Delta\chi^2_{MH}$ a function of L

CONCLUSION

This project was a simple approach but represented a step by step modeling of the JUNO experiment. The whole process of the experiment has been implemented in `C++` [4], from the source to the detector and its optimal position, using simplifications.

[1] JUNO Collaboration, *Neutrino Physics with JUNO*, 18 Oct 2015,`http://arxiv.org/abs/1507.05613v2`

[2] JUNO Collaboration, *Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO*, 28 Apr 2022, `https://arxiv.org/abs/2204.13249`

[3] L. Ahan,Y. Wang,J. Cao,L. Wen *Determination of the Neutrino Mass Hierarchy at an Intermediate Baseline*,26 Nov 2008, `https://arxiv.org/abs/0807.3203`

[4] R. GUITTON, F. TOUCHTE-CODJO,*JUNO TIPP GIT* `https://github.com/roronoarapha/JUNO/`