Physics with JUNO

CNRS/IN2P3 2020 Prospect on Neutrino Physics

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September 20, 2019

Reactor neutrinos have been an important class of experiments for both discovery and precision measurement in the history of neutrino studies. Since the first generation of reactor neutrino experiments in the 1950s with Reines and Cowan, the detector technology has greatly advanced. The current experiments, Daya Bay, Double Chooz and RENO have led neutrino physics into the precision era (a few %). The Jiangmen Underground Neutrino Observatory (JUNO) is designed to study neutrino mass ordering and measure three of the neutrino oscillation parameters with high precision (towards sub-percent) using reactor neutrinos. Many other physical phenomena, including supernova neutrinos, solar neutrinos, geo-neutrinos, atmospheric neutrinos can be studied with JUNO through differents detection channels. The CNRS/IN2P3 teams involved in the JUNO experiment here highlight the JUNO potential for physics in terms of possible impact and synergy to other research fields.

Preamble

The Jiangmen Underground Neutrino Observatory (JUNO)[1] is a 20 kton multi-purpose underground liquid scintillator detector, similar to KamLAND and Borexino, located in China. Nuclear reactors 53 km far away from the detector, are the neutrino source for JUNO. The JUNO detector provides the necessary size to address simultaneously several important physics challenges. The excellent energy resolution and the large fiducial volume anticipated for the JUNO detector offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics. A non-negligible challenge lays inside the central detector, surrounded by muon detectors (a Top Tracker and a water Cherenkov Outer Veto). The target volume, where neutrinos detection takes place, is read out by a double PMT system, using 18,000 20" PMTs (labelled Large PMT system) and 25,600 3" (labelled Small PMT system) PMTs. The JUNO international collaboration consists of 77 institutes around the world (600 collaborators).

One of its purposes is the determination of the neutrino Mass Ordering (MO), which is one of the main open questions of neutrino physics. JUNO will look at the oscillation frequencies at the first oscillation maximum defined by θ_{12} and Δm^2_{21}, where the discrimination for the MO choice is enhanced. To determine the MO, JUNO aims to resolve the neutrino spectrum wiggles (due to θ_{13} and Δm^2_{ee}). Indeed, their phase discriminates between Normal and Inverted Ordering (NO and IO). For that purpose, an outstanding 3% energy resolution at 1 MeV must be achieved. It is expected that after six years of operation, JUNO will reach a sensitivity between 3 to $4\,\sigma$ on the MO determination. Moreover, the measurement of the antineutrino spectrum with excellent energy resolution will also lead to the precise determination of the neutrino oscillation parameters $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{ee} to an accuracy better than 1%, which will play a crucial role in the future unitarity test of the PMNS matrix. JUNO will obverse for the first time the two oscillation patterns, the one lead by Δm^2_{21} and the other by Δm^2_{ee}, since so far all the experiments observed an oscillation pattern that could be approximated by the two flavor case. The data taking is to start by 2022.

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Neutrino Oscillation Physics

As discussed before, neutrino oscillations are a core topic of JUNO. With all recent advances in neutrino oscillation measurements in the past decades, we started getting a more complete picture of the neutrino oscillations. However, there are mainly two main unknowns: the neutrino mass ordering, that is which neutrino is the lightest, and the CP violating phase in the neutrino sector. JUNO will be able to determine the neutrino mass ordering with 6 years of data taking with a 3 σ significance by itself. Early studies indicate it should reach beyond 5 σ significance in combination with other experiments such as KM3NeT-ORCA [2] and IceCube [3], in a similar time frame. The discovery of the neutrino mass ordering will have important phenomenological consequences for the supernova neutrinos, cosmology as well as for atmospheric and accelerator neutrinos propagating in the matter of the Earth. The ordering is important whenever the matter effects on oscillations are driven by the 1-3 mixing and corresponding mass splittings [4]. Its determination may provide the key to establish the relationship among the lepton masses and mixing. The extraction of the neutrino mass ordering is a data-driven field expected to evolve very rapidly in the next decade, starting with JUNO and KM3NeT-ORCA neutrino experiments. Since neutrino oscillation measurements, cosmological observations and neutrinoless double beta decay experiments are cornering the inverted mass ordering region, it makes sense to combine their results. In addition, it should help the discovery of the CP violating phase and serve as guide for neutrinoless double beta decay searches.

Even after the discovery of the neutrino mass ordering and the CP violating phase, there will be significant room for probing the lepton mixing framework, to make it as precise as the quark mixing one. Therefore, there is still significant room for new physics. Probing the consistency of the lepton mixing framework will require high precision measurements of several oscillations parameters in order to both check the unitarity of the mixing matrix and verify the relation between the oscillation frequencies in neutrino mixing. The latter is tied to the $\Delta m^2_{32} + \Delta m^2_{21} = \Delta m^2_{31}$ relationship among the neutrino mass squared differences. JUNO will be able to measure for the first time both solar and atmospheric neutrino oscillations at the same time using reactor anti-neutrinos. JUNO will measure with a sub-percent precision for the first time one mixing angle and the two mass squared differences. While reaching the same level as the checks done to the mixing of quarks is still far in the future, JUNO's measurements will be a corner stone for testing both the unitarity of the lepton mixing matrix and the relationship between neutrino oscillation frequencies.

All results discussed above will be obtained via the study of reactor electron antineutrino disappearance. In addition to studying neutrino oscillations using neutrinos from reactors, JUNO will also be able to probe neutrino oscillations from other neutrino sources. In case JUNO observes a supernova, it will be possible to make an independent determination of the neutrino mass ordering. In this case, the ordering will change how matter affects neutrino oscillations and change the observed neutrino spectra from the supernova. Even if neutrino oscillation measurements with these other sources do not reach the precision obtained from reactor antineutrinos, they will still constitute an important verification of the consistency of the neutrino oscillation framework, within a single detector. Searches for light sterile neutrinos with JUNO will also be possible by augmenting the detector by either adding a source to the center of the detector, or by adding a cyclotron-drive source (IsoDAR) located close to JUNO, however their realisation will be dependent on results from current light sterile neutrino experimental searches.

The CNRS/IN2P3 groups have strong interest in the neutrino oscillation physics, and have previous experience with having performed neutrino oscillation analyses previously in several different experiments.

Astrophysics

With its huge target mass, the low-energy threshold and the unprecedented energy resolution and energy scale precision, JUNO is a competitive detector for astrophysical programs, such as galactic core-collapse supernova neutrinos (CCSN), diffuse supernova neutrino background (DSNB) and solar neutrinos. In the CCSN, a massive star with masses above eight solar masses is expected to collapse under its own gravity and then to explode emitting 99% of its binding energy in the form of a neutrino burst [5]. Astrophysical models predict a rate of CCSN of about three per century in our galaxy, the last one being in 1987, with a distance distribution peaked in the region of ten kpc (e.g. [6]). At these distances, at least one SN is expected during the operation time of JUNO. The precise determination of the energy spectrum and its flavour and time evolution would allow us to infer parameters of interests for astrophysics, nuclear physics and particle physics (mass ordering, constraints on absolute neutrino masses, sterile neutrinos or possible new physics). The number of events varies between up to millions depending on the SN distance ($\sim$ 6000 at 10 kpc) and the detector will be sensitive to different neutrino (antineutrino) flavors and interaction channels, the dominant IBD process as well as neutral- and charge-current interactions on ^{12}C and elastic scattering on electrons and proton [7]. The possible detection of O(100) pre-SN neutrinos would also be possible and is investigated as valuable warning system and for the study of stellar models[10]. JUNO is thus part of the SNEWS project (Supernova Neutrino in the Multi-messenger Era) which involves an international collaboration of experiments (e.g. Super-K, Ice Cube, Borexino, Kamland...) to provide the community a prompt alert of a CCSN.

Multi-wavelength astronomy has been successfully exploited for decades helping to understand better particle acceleration occurring in sources. The IN2P3 is fully involved in this field. Coincidence detection between different instruments improves discovery potential, and will aim to understand what happens in a core collapse supernova before the light and neutrinos escape. The classic multi-messenger astronomical events are neutrinos (prompt), Electromagnetic (delayed) and Gravitational Waves (GW, prompt) but there is a risk that the optical signature (EM) may be obscured [8], consequently only neutrinos and GWs directly probe physics of core collapse. The IN2P3 is very well positioned to study these multi-messenger events with the LIGO-VIRGO experiment, the gamma-ray experiments (HESS, CTA) and through JUNO or KM3Net experiments for detecting neutrinos as messengers of the invisible world [9].

In addition DSNB is the flux of neutrinos from past core-collapse SN in the visible Universe and can be detected by JUNO. Its measurement provides information on the star formation rate, the average CC neutrino spectrum and the rate of failed SN. This topic is not a priority involvement of the IN2P3 teams.

Also solar neutrinos can be studied with the JUNO detector. One of the major concerns in solar neutrino physics is the so called solar metallicity problem (SMP), about the content of metals in the core of the Sun [11]. To this purpose, JUNO can contribute with an improved accuracy in the determination of the ^{7}Be and ^{8}B flux. However, for solar neutrino observations, the radiopurity requirements are more strict than for the MO determinations. This topic is likely to become important if the possibility to measure solar neutrinos with JUNO is reached. The IN2P3 will be able to maintain its involvement in the solar neutrino field.

Proton Decay Searches

The large target mass of the JUNO detector allows searches for protons decays to reach valuable sensitivities. This is a way to probe physics beyond the Standard Model (SM). Indeed, in the framework of the SM, no observable baryon number violation is allowed. This is, however, a generic prediction of Grand Unified Theories (GUTs). Among the channels predicted by various models, 2 are of particular interest : $p \to e^+\pi^0$ and $p \to K^+\bar{\nu}$. The former is dominant in many models, the latter is one of the main kaonic channels, which sign SUSY GUTs. JUNO possesses no obvious advantages over other large scale neutrino detectors to select $p \to e^+\pi^0$ efficiently. In the case of $p \to K^+\bar{\nu}$, however, JUNOs impact could be real. This decay can be searched via the leptonic kaon decay mode $K^+ \to \mu^+ (\to e^+\nu)\, \nu$. Its signature is therefore the presence of 3 signals in coincidence : the K^+ energy deposit, followed in average 12 ns later by the μ^+ energy deposit, about 2 μs before the appearance of a Michel positron. The K^+ and μ^+ fixed energies are another handle. The ability to reconstruct the K^+ is the key point here. It is not possible for Hyper Kamiokande since this kaon is below the Cherenkov threshold. To exploit the timing pattern mentioned above, a sophisticated reconstruction is necessary [1, 12], due to the short K^+ lifetime, that will often cause the K^+ and μ^+ signals to overlap. French groups could build on their experience of liquid scintillator detectors to take part in this search. In the long run, JUNOs sensitivity might not be able to match that of Hyper Kamiokande or DUNE. However, it will start taking data several years before and could therefore be the first to obtain a 3σ observation : this significance can be obtained after 10 years if $\tau/B(K^+\bar{\nu}) = 10^{34}$ years [1, 13], a value typical of SUSY GUT models (the present lower limit is 7×10^{33}). A first hint at JUNO is anyway plausible. Synergy with DUNE and Hyper-Kamiokande, hence potentially with French groups, is expected. A hint in JUNOs data would probably trigger an increased analysis effort in these collaborations. More generally, working on this decay would complement searches carried out by French groups, e.g., at colliders to obtain a complete scope of promising searches for BSM physics.

Nuclear Physics

The experimental site that will host JUNO detector is at 53 km from 2 Nuclear Power Plants (NPP). Yangjiang NPP has 6 2nd generation pressurized water reactor cores of 2.9 GWth each. Taishan NPP has planned four cores from the 3rd generation pressurized water reactors EPR of 4.59 GWth each. JUNO will be also sensitive to other NPP at a distance of about 215 km and which will contribute to about 2.8% of the reactor antineutrino events. Recent reactor neutrino experiments such as Daya Bay, Double Chooz and RENO have detected large statistics of antineutrinos from low-enriched (LEU) pressurized water reactors and produced precision measurements of their average energy spectrum and flux. These data provide unique independent constraints on the production and properties of rare neutron-rich isotopes in nuclear reactor and allow the observation of the change in the reactor antineutrino spectrum and flux as a function of fuel evolution. The good energy resolution of JUNO will help on the understanding of the LEU antineutrino spectrum in particular for the still non-understood overall spectrum distortion observed, dominated by a 5 MeV excess (or bump). The observed spectral distortion is not a danger for the determination of the neutrino mass ordering, however a not known antineutrino spectrum fine structure can have an impact on its determination. Consequently, the JUNO collaboration has decided to construct a high-resolution antineutrino detector at 30-35 meters from one Taishan reactor cores (TAO for Taishan Antineutrino Observatory) in order to provide a reference spectrum for JUNO to remove model dependencies by measuring fine structures and also to provide a benchmark for the inspection of nuclear data. The TAO detector will be a 2.6 ton-gadolinium-doped Liquid Scintillator contained in a spherical acrylic vessel and viewed by 10 m^2 SiPM (silicon photomultiplier). A resolution of 1.5%/PE at 1 MeV is required and a statistics of around 2000 events per day is expected. This detector constructed for JUNO neutrino mass ordering determination has a large span physics interest in particular for the nuclear community. Indeed these data will help to do a better comparison with the models to guide the identification of incorrect/incomplete nuclear datasets and modelling inputs for dominant fission products or impose new constraints on the properties of several isotopes. Moreover the possibility to have datasets from different reactor fuel compositions will allow to investigate separately for the primary fission isotopes (^{235}U, ^{239}Pu, ^{238}U). A useful help on the theoretical advances can be brought : investigation of the systematic uncertainties associated from the conversion of the integral beta spectra measured at the high flux reactor ILL and improvement of the spectra determined from the summation method thanks to the measurement of beta decay properties of fission products with the Total Absorption Gamma-ray Spectroscopy (TAGS) technique.

CNRS/IN2P3 and CEA are strongly involved in the determination of the antineutrino flux and spectrum produced by reactors and TAGS measurement for nuclear decay data. TAO data will be available for all the collaboration, they look very interesting for a better understanding of the reactor antineutrino flux and spectrum for fundamental physics, for safeguards and monitoring applications. They will enrich the nuclear data and will improve reactor models that enable predictions. A possible work on these data by the french teams could be considered in synergy with nuclear data IN2P3 and CEA physicists.

Double-Beta Decay

The determination of the nature of the neutrino (Dirac or Majorana) via the neutrino-less double beta decay process ($0\nu\beta\beta$) in the JUNO experiment. This physics case is not yet considered in the JUNO as the main phase, starting in 2022, focused on the determination of the neutrino mass ordering. But it may become the main goal of the JUNO experiment in a hypothetical second phase >2030. In this second phase, the idea is to insert into the central region of the JUNO detector a balloon filled with enriched xenon gas with ^{136}Xe up to 80%) dissolved in an ultra-pure liquid scintillator. The two main advantages of JUNO are the energy resolution ($3\%/\sqrt{E}$ i.e. 1.9% σ at the Q-value of ^{136}Xe) and the powerful shielding from the 35 m diameter liquid scintillator. A study has been performed in 2017 in order to evaluate the JUNO sensitivity to $0\nu\beta\beta$ studies [14]. Taking into account the main backgrounds with realistic assumptions ($2\nu\beta\beta$ process, solar neutrinos from ^{8}B, muon induced radio-nuclides, radioactivity of the liquid scintillator at the level of 10^{-17} g/g in U/Th), a background index of 1.35 evt/ROI/ton/year (ROI[1] of 110 keV) has been estimated. Assuming 5 tons of fiducial ^{136}Xe) target mass and 5 years live time, a 90% C.L sensitivity of $T_{1/2}$ (or $m_{\beta\beta}$) to be $\sim 5.6\times 10^{27}$ yr (or 8-22 meV) may be achieved. In the case of 50 tons of fiducial ^{136}Xe (not realistic up to now but it helps to demonstrate that the sensitivity could really scale with target mass), the 90% C.L sensitivity of $m_{\beta\beta}$ can scale up to (5-12 meV), which is well below the region allowed by the scenario of inverted neutrino mass ordering. In an inverted mass ordering scenario, JUNO would be able to prove the nature of the neutrino by observing (Majorana) or not observing (Dirac) a ($0\nu\beta\beta$) event from ^{136}Xe. Another promising isotope to be considered in the future is ^{130}Te even if some drawbacks have to be investigated. This technique is currently used in the KamLAND-Zen and SNO+ experiments without IN2P3 teams involved. In the future, IN2P3 expertise in term

[1]The ROI (or Region of Interest) stands for the optimised energy window around the Q-value scrutinised for the $0\nu\beta\beta$ signal observation.

of radiopurity, calorimetry and data analysis may help to join such double beta project with a high visibility.

Conclusion

There are still key unknown parameters in the neutrino sector. It is a key issue in our understanding of physics today. JUNO is one of the major experiments in neutrino oscillations using reactor neutrinos with high precision, capable to measure the mass ordering and being a first step towards unitarity test. The synergy with DUNE and HK and other past experiments will be important, as highlighted here. Detector specifications (size, energy resolution, baseline, overburden, etc) enables JUNO to do physics beyond only reactor neutrino physics, thus addressing the proton decay measurement, astrophysics and possibly in the future also double-β detection.

CNRS/IN2P3 is in strong position to the JUNO experiment for physics upon data taking as technical tasks are to be completed within the next $\sim$1.5 years, mainly in the SPMT and Top-Tracker systems. Due to its leading role on these two JUNO systems and its active contribution on the associated simulation codes, the IN2P3 will be particularly well positioned to lead several analysis tasks related to these systems and therefore to contribute to the physics mentioned in this document. JUNO is conceived and planned to mark significant breakthrough for the ultimate quest of the neutrino properties.

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