EPJ Web of Conferences **136**, 04001 (2017) DOI: 10.1051/epjconf/201713604001
RICAP16

Status and prospects of the JUNO experiment

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Abstract. The JUNO Jiangmen Underground Neutrino Observatory, a 20 kton multi-purpose underground liquid scintillator detector, has been proposed and approved for realization in the south of China. In this work I describe first the broad physics capabilities of the experiment, which include the crucial measure of the neutrino mass hierarchy, the high precision determination of three oscillation parameters, and a rich astroparticle program. Then, I give the details of the mass hierarchy determination procedures and an outlook on the progress and schedule of the experiment.

1 Introduction

In the global context of the future neutrino oscillation studies, the JUNO detector [1] will play a central role on two aspects: the determination of mass hierarchy and the precise measurements of the solar oscillation parameters, i.e. Δm^2_{21}, $sin^2\theta_{12}$, as well as of the atmospheric squared mass difference Δm^2_{31}.

JUNO is designed and realized as a huge liquid scintillator detector, therefore exploiting a mature and well proved technology, which has already provided fundamental contributions to the neutrino oscillation study through several implementations (Borexino [2], KamLAND [3], Daya Bay [4], Reno [5] and Double Chooz [6] being the most recent examples). It will base its measurements on the detection of the global antineutrino flux coming from the cores of two nearby nuclear complexes, Yangjiang and Taishan, located at about 53 km from the experimental site.

The program will be complemented by an ensemble of astroparticle physics measurements, which will significantly enhance the physics potential of JUNO.

2 Summary of characteristics and of physics goals

JUNO will join the renowned, long tradition family of reactor neutrino experiments based on the scintillation technology, whose first well known example was the Savannah River experiment, with which Cowan and Reines revealed for the first time the (anti)neutrino particle.

In Fig. 1 there is the summary of reactors' results accumulated so far, expressed as ratio of observed over expected events, contrasted with the prediction from the oscillation survival probability function. On the horizontal axis the reactor-detector distance is reported; the plot shows the well-known fact that at small distance the impact of the oscillation phenomenon on the detector count rate

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is not visible, while it starts to manifest from roughly little less than 1 km baseline. At the special distance of 53 km the count rate suppression, mainly driven by the solar oscillation parameters, is maximal, therefore creating the best condition to study the interference effect governed in turn by the atmospheric mass squared difference, which is responsible for the ripple superimposed on the count rate suppressed profile. This is, therefore, the rationality beyond the choice of the optimum site and distance between JUNO and the emitting anti-neutrino cores.

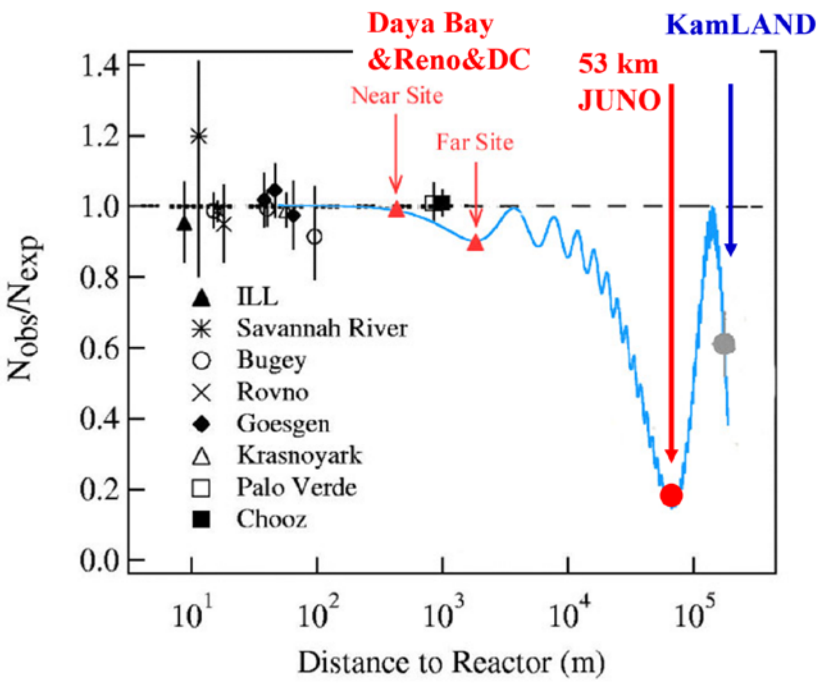

Figure 1. Summary of past reactors' results as ratio of observed to expected count rate, together with the predicted JUNO point.

To fully exploit this optimal baseline, in order to perform an effective and successful measurement of the mass hierarchy, the detector must be endowed with two essential characteristics: large mass to perform a high statistic measurements, and stringent energy resolution to clearly distinguish the ripple induced by the atmospheric mass squared term. The two key numbers in this respects are the total mass of 20 kton of liquid scintillator, and the energy resolution of 3% at 1 MeV, which represent, therefore, the major technical features which characterize the experiment.

In term of physics reach, JUNO thanks to its large mass can tackle a plurality of measurements. Beyond mass hierarchy and precision determination of neutrino oscillation parameters, it can provide fundamental results concerning many hot topics in the astroparticle field. An incomplete list comprises supernova burst neutrinos, diffuse supernova neutrinos, solar neutrinos, atmospheric neutrinos, geo-neutrinos, sterile neutrinos, nucleon decay, indirect dark matter search, as well as a number of additional exotic searches, as thoroughly illustrated in the physics program of the experiment (yellow book), published in [7].

3 Basic features of the program: detector structure, location and Collaboration

In term of implementation characteristics, JUNO is a spherical unsegmented liquid scintillator detector that will push such a technology beyond the present limit, as far as the mass (20 kton) and the resolution (3%) are concerned. Succinctly, the detector can be described as a large spherical acrylic vessel, which will hold the scintillator volume, contained in turn in a water pool, to ensure adequate shielding against the gamma radiation and neutrons from the rock.

The vessel will be surrounded by a stainless steel truss which will perform the twofold task to sustain the vessel, by relieving its internal stress, and to provide the anchor support for the 18000 20” photomultipliers observing the scintillation photons. The light detection system will comprise also an additional set of 3” PMTs, up to 36000, which will be used for calibration purpose and to cross check the performances of the main PMTs, with the scope to control and reduce the systematic effects of the measurements performed by the main 20” PMT system.

Moreover, the shielding water around the acrylic vessel will be converted into a Cherenkov detector, being instrumented with about 2000 phototubes, which will detect the muon induced Cherenkov light. Such an arrangement, together with the top tracker that will be deployed on the roof of the detector itself, will allow an efficient muon veto capability, an essential feature at the planned shallow depth of the experiment, i.e. 700 m.

JUNO has been approved in China at the beginning of 2013 and has been later joined by groups from all over the world. Currently the Collaboration encompasses 66 institutions from Asia, Europe and America, with more than 450 researchers, and it is still expanding.

The experiment is located in the South of China, Guangdong province, Jianmeng County, Kaiping city, at 53 km from the two sites of Yangjian and Taishan, where 6 and 4 nuclear cores are planned, respectively. By 2020 according to the construction schedule of the plants 26.6 GW will be installed (2 cores will be missing at Taishan), while eventually the total power of 35.8 GW will be available.

4 How to infer the mass hierarchy

The observable quantity from which the mass hierarchy will be inferred is the positron spectrum detected in the liquid scintillator, stemming from the Inverse Beta Decay reaction through which antineutrino detection will occur. Specifically, the determination of the mass hierarchy relies on the identification on such a spectrum of the “imprinting” of the anti-ν_e survival probability.

The Inverse Beta Decay Reaction a là Cowan Reines is the following

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

The energy deposited by the positron in the scintillator, i.e. its kinetic energy plus the total 1.022 keV energy of the two annihilation gammas, reflects faithfully the energy of the incoming anti-neutrinos

$$E_{vis}(e^+) = E(\nu) - 0.8\,MeV \tag{2}$$

$E_{vis}(e^+)$ is, thus, the specific measurement output to be analyzed for the hierarchy evaluation.

The time coincidence (mean difference of the order of 250 μs) between the positron event and the γ ray from the subsequent neutron capture on protons allows to identify effectively the occurrence of neutrino detection and to pick up the positron scintillation signal, even in presence of uncorrelated background.

In order to describe the specific algorithm through which the MH can be unraveled, we resort to the electron (ant)neutrino survival probability, which in a full three flavor framework can be written as

$$P_{ee} = 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2(\Delta_{21}) - sin^2\theta_{13} sin^2(|\Delta_{31}|) - \\ sin^2\theta_{12} sin^2 2\theta_{13} sin^2(\Delta_{21}) cos(2|\Delta_{31}|) \pm \frac{sin^2\theta_{12}}{2} sin^2 2\theta_{13} sin(2\Delta_{21}) sin(2|\Delta_{31}|) \tag{3}$$

exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$, and assuming

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

The sign flip in front of the last term of eq. (3) is due to the hierarchy: positive for direct hierarchy, negative for the inverse one. The presence in this term of the multiplicative factor $sin^2 2\theta_{13}$ questioned the effectiveness of this methodology, proposed for the first time in [8], until the θ_{13} experimental determination from Daya Bay, Reno and Double Chooz. Indeed, should θ_{13} have been resulted close to 0, the last term of the P_{ee} expression would have been vanishing small, making the proposed approach unfeasible. In reality, the discovery that θ_{13} is actually very close to the previous Chooz limit [9], opened the door to the actual implementation of the method.

The effect of P_{ee} on the reactor spectrum is shown in Fig. 2; the y axis is proportional to the event rate, while on the x axis the ratio L/E_nu is reported. The dashed line is the un-oscillated spectrum; the continuous black line is the spectrum distorted and suppressed as effect of the “solar” oscillation: it is this large effect the key for the very precise determination of the two “solar” mixing parameters Δm_{21}^2 and $sin^2\theta_{12}$.

The blue and red lines superimposed on the smooth black line, instead, display the effect of the interference term driven by the atmospheric mass squared difference. The frequency of the ripple depends on $|\Delta m_{31}^2|$ (which therefore can also be determined with high accuracy from the precise “tracking“ of the ripple itself), while its phase is linked to the MH, as shown by the reciprocal shift of the blue and red lines in the figure. Unraveling the phase of the ripple, hence, is the clue for the MH determination. Quantitative assessments show that this method can lead in JUNO to a 4σ discrimination capability between the true and wrong hierarchy in 6 years of data taking.

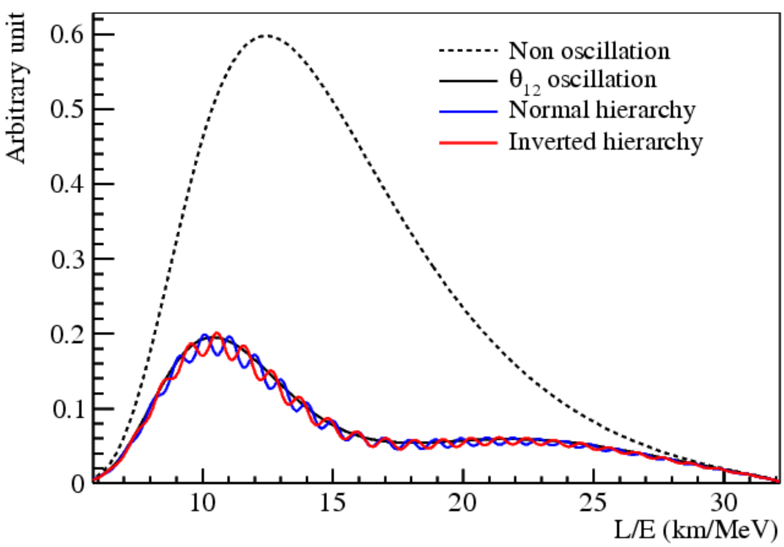

Figure 2. Effect of Pee electron neutrino survival probability on the reactor spectrum.

5 JUNO progress and schedule

The experiment is scheduled to start data taking in 2020. The ground breaking signalling the start-up of the excavation occurred in January 2015. So far, more than half of the slope tunnel (900 out of 1340 m) and about half of the vertical shaft (300 out of 611 m) have been excavated. The former will allow to bring the scintillator underground, the latter will enable access of personnel and construction materials.

The civil construction is foreseen to be completed by about middle of 2018, included the large experimental hall. The preparation of the detector components, e.g. phototubes, acrylic panels, etc., has started in the current year 2016 and will encompass the whole 2017 and part of 2018, while the global onsite installation will be completed by the end of 2019. All this is in line to ensure scintillator fill and start-up of data taking within the targeted 2020 year.

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