Status and perspectives of the JUNO experiment

Gioacchino Ranucci on behalf of the JUNO Collaboration

Istituto Nazionale di Fisica Nucleare
Via Celoria 16
20133 Milano - Italy

Gioacchino.ranucci@mi.infn.it

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. After an intense design phase, the overall concept of the structure of the detector has been finalized, paving the way towards the construction of the several components and subsystems, which will compose it. Meanwhile, the excavation of the site which will host the experiment has been started and is rapidly progressing. The main physics target of JUNO is the determination of the neutrino mass hierarchy, which will be accessible through the measurement of the pattern of antineutrino spectrum from two high power nuclear complexes under installation 53 km away from the experimental site. In this work I describe the broad physics capabilities of the experiment, which include in addition to the crucial measure of the neutrino hierarchy the high precision determination of three oscillation parameters, as well as a rich astroparticle program, and I illustrate the main technical characteristics of the detector.

1. Introduction

The successful saga of neutrino oscillations, culminated in the 2015 Nobel Prize, paves the way to a future, rich and diverse experimental program of precision experiments tasked to complete the determination of the elements of the PNMS oscillation matrix with unprecedented accuracy, and to unravel the yet undiscovered features of neutrino properties. Therefore, mass hierarchy (MH) determination, octant of $\theta_{23}$, violating $\delta_{CP}$ phase and improved precision of the mass-mixing parameters (mixing angles as well as squared mass differences), are the core of the ambitious worldwide neutrino oscillation program shaped for the forthcoming two decades. At the same time the Dirac or Majorana nature of the neutrino mass term, together with its absolute value, will be probed by a suite of dedicated experiments.

In this global context, 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. $\Delta m_{21}^2$, $\sin^2 \theta_{12}$, as well as of the atmospheric squared mass difference $\Delta m_{31}^2$.

JUNO will be 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 experiments (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 nearby nuclear complexes.

The program will be complemented by an ensemble of astroparticle physics measurements, which will significantly enhance the physics potential of JUNO.
Overall requirements, technical features and the current status of the experiment are described in the following.

2. Summary of characteristics and of physics goals

JUNO will be a new member of 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.

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

In Figure 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 displayed; the plot reports the well-known fact that at small distance the impact of the oscillation phenomenon on the detector count rate is not visible, while it starts to manifest from slightly less than 1 km baseline. At the 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.

To fully exploit this optimal baseline 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, such a high mass detector 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, like 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 terms 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. Briefly, the detector (see Figure 2) 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.

![Figure 2. Schematic view of the JUNO configuration](image)

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 25000, which will be used mainly for calibration purpose (the additional coverage is minimal) 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 used as 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. about 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 71 institutions from Asia, Europe and America, with more than 500 researchers, and it is still expanding.
The experiment is located in the South of China, Guangdong province, Jiameng 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 “inprinting” of the anti-ν_e survival probability P_{ee} on such spectrum.

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

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

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

\[ E_{\nu_{\text{vis}}}(e^+) = E(\nu) - 0.8 \text{ MeV} \]

\( E_{\nu_{\text{vis}}}(e^+) \) is, thus, the specific measurement output to be analysed 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.

It can be shown that through suitable approximations the survival probability P_{ee} can be written as:

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

The sign flip in front of the last term is due to the hierarchy: positive for direct hierarchy, negative for the inverse one. The presence of the multiplicative factor \( \sin^2 \theta_{13} \) in this term questioned the effectiveness of this methodology, proposed for the first time in [8], until the experimental determination of the \( \theta_{13} \) (about 8°) by Daya Bay, Reno and Double Chooz. Indeed, with \( \theta_{13} \) very close to 0, the last term of the \( P_{ee} \) expression would have been vanishing small, making the proposed approach unfeasible. Since instead \( \theta_{13} \) is actually almost coincident to the previous Chooz limit [9] and thus sizably different from 0, the method is realizable in practice.

The effect of \( P_{ee} \) on the reactor spectrum is shown in Figure 3; 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 an effect of the “solar” oscillation: this large effect is the key for the very precise determination of the two “solar” mixing parameters \( \Delta m^2_{21} \) 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 \( |\Delta m^2_{31}| \) (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.
Figure 3. Effect of $P_{ee}$ electron neutrino survival probability on the reactor spectrum

However essential prerequisite to accomplish meaningfully the hierarchy determination is the energy resolution: while in an ideal antineutrino spectrum computed for infinite resolution throats and peaks induced by the electron neutrino survival probability are perfectly visible, in a concrete measured spectrum these features are significantly smoothed as effect of the detector resolution.

For example, below 3% at 1 MeV of energy resolution, throats and peaks in the measured spectrum are still distinguishable and consequently the discrimination between the two hierarchies feasible. If, instead, the same measure would be performed with 5 or 6% resolution, which are the values of the state of the art liquid scintillator technology of large scale experiments, peaks and throats would completely disappear, making any attempt to unravel the hierarchy impossible. From several numerical evaluations it stems that the 3% energy resolution considered in this example is just the limit value above which the hierarchy discrimination can be meaningfully performed and is therefore assumed as the design goal of the experiment, representing by far its greatest challenge in term of improvement over past experiences.

Realistic $\chi^2$ calculations performed with the input parameters related to JUNO detector and site (i.e. baseline 53 km, fiducial volume 20 kt, thermal reactor power 36 GW, exposure time 6 years, proton content 12%, energy resolution 3%) indicate that the statistical discrimination power of the experiment amounts to a $\Delta \chi^2$ equal to 16 between the true and wrong hierarchy hypothesis.

However, if systematic effects are considered, there is unavoidably a loss of discrimination power. The most important effect in this sense is the non-exactly equal baselines from the nuclear cores to the experiment, characterized by a spread of about 500 m, which is responsible for a loss of 4 of the $\Delta \chi^2$ indicator. Other adverse effects detrimental to the discovery power are the 1% shape uncertainty of the reactor spectrum, and the background uncertainty (rate 4.5%, shape 0.35%). All in all, these effects bring the discrimination power down to $\Delta \chi^2 = 10.4$.

On the other hand, a recovery of this loss can be obtained including in the $\chi^2$ analysis the a-priori information on the value of the atmospheric mass square difference, which will be available from the LBL experiments with 1% precision at the time of the JUNO data release. Such an information can be best incorporated through the effective mass square difference, $\Delta m^2_{\text{eff}}$, as defined in [10]. The net effect of this analysis approach is to recover a value of about 8 in the $\Delta \chi^2$, bringing back the discovery power of the experiment to the $\Delta \chi^2=16$ realm.

5. Precision measurement of oscillation parameters and other physics reaches
The huge effect of the survival probability on the reactor spectrum and the large amount of data that will be accumulated (JUNO plans to record 100000 events in 6 years of data taking) make it possible to measure three of the mass-mixing parameters with unprecedented sub-percent precision: the two solar parameters $\Delta m^2_{21}$ and $\sin^2\theta_{12}$, and the effective parameter $\Delta m^2_{ee}$ defined as (see [10]) $\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$.

From pure statistical considerations, the uncertainty of the measurements of these parameters is predicted to be very limited, i.e. 0.54%, 0.24% and 0.27% for $\sin^2\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{ee}$ respectively, taking also into account the correlation among them. Even adding background and several systematic effects, like the spectrum bin to bin uncertainty, 1%, the uncertainty on the absolute energy scale, 1%, and the energy non linearity, again 1%, the overall errors on the parameters remain below the 1% target: 0.67% for $\sin^2\theta_{12}$, 0.59% for $\Delta m^2_{21}$, and 0.44% for $\Delta m^2_{ee}$.

For lack of space, I do not report here the results of many studies carried out to assess quantitatively the JUNO capabilities with respect to the several chapters of its vast astroparticle program, which are all illustrated in details in the already cited yellow book [7].

6. JUNO progress and schedule

The experiment is expected to start data taking at the beginning of the next decade. The ground breaking signaling the startup of the excavation occurred in January 2015. So far, the slope tunnel (1266 m) and the vertical shaft (564 m) have been fully excavated. The former will allow to bring the scintillator underground, the latter will enable access of personnel and construction materials. The excavation is now progressing towards the location where the experimental hall will be realized.

The civil construction is foreseen to be completed by about middle of 2019. The preparation of the detector components, e.g. phototubes, acrylic panels, etc., has started in the past year 2016 and will encompass the whole 2017 and 2018, and part of 2019, while the global onsite installation will be completed by the end of the current decade. All this is in line to ensure scintillator fill and startup of data taking at the beginning of the next decade.

7. Conclusion

The vast potential physics reach of very large liquid scintillator detectors, mass hierarchy determination and beyond, is the foundational motivation of JUNO conceived and planned to mark significant breakthroughs for the ultimate quest of the neutrino properties.

The Collaboration is rapidly progressing toward the construction of the detector with all the important design decisions already taken, the prototyping phase marking important steps forwards for all the subsystems and with the excavation of the site going ahead.

The JUNO exciting science program will start at the dawn of the next decade, when the experiment will be filled.

References
[1] Adam T et al. (JUNO Collaboration) 2016 The JUNO Conceptual Design Report arXiv:1508.07166
[2] Alimonti G et al. (Borexino Collaboration) 2009 Nucl. Instr. and Meth Meth. A vol 600, p 568
[3] Abe S et al. (KamLAND Collaboration) 2008 Phys. Rev. Lett. vol 100, p 221803
[4] An F P et al. (Daya Bay Collaboration) 2012 Phys. Rev. Lett. vol 108, p 171803
[5] Ahn J K et al., (RENO Collaboration) 2012 Phys. Rev. Lett. vol 108, p 191802
[6] Abe S et al., (DOUBLE CHOOZ Collaboration) 2013 Phys. Lett. B vol 723, p 66
[7] An F P et al. (JUNO Collaboration) 2016 J. of Phys. G (Nucl. and Part. Phys.) vol 43, p 030401
[8] Petcov S T and Piai M 2002 Physics Letters B vol 553 pp 94-106
[9] Apollonio M et al. (Chooz Collaboration) 2003 The European Physical Journal C vol 27, pp 331-374
[10] Nunokawa H, Parke S, Zukanovich Funchal R 2005, Phys.Rev.D vol 72, p 013009