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Status of the JUNO experiment

A. Paoloni[a,*] on behalf of the JUNO collaboration

[a] INFN-LNF,
Via E. Fermi 54 -00044, Frascati (Roma), Italy

E-mail: alessandro.paoloni@lnf.infn.it

JUNO is an experiment conceived primarily to study neutrino oscillations of electron antineutrinos emitted by nuclear power plants, in order to infer the neutrino mass hierarchy from the oscillated neutrino spectrum at a baseline of about 50 km, exploiting an unprecedented energy resolution of 3% at 1 MeV.
It is composed of 20 kton of high purity liquid scintillator, read-out by a dual system: the 17612 20-inch large LPMT system (LPMT), and the 25600 3-inch small PMTs (SPMT). The experiment is also endowed with a Water Cherenkonv Veto and a Top Tracker, made by scintillator strips, to control the background due to cosmic rays. A reference detector, TAO (Taishan Antineutrino Observatory), at a short baseline from one of the reactor cores, will be built, also based on the liquid scintillator technology but with the light read-out by SiPM (Silicon Photomultipliers), in order to improve the energy resolution.
The large mass of JUNO, together with the performances of its detectors, will allow to precisely measure at sub-percent level several oscillation parameters (θ_{12}, Δm^2_{21}, Δm^2_{31}). JUNO will be also an excellent observatory for solar, atmospheric, SuperNova and geo-neutrinos. Other beyond-the-Standard-Model searches, such as the proton decay, will also be at reach.

In this paper the experiment design will be described and the installation status reported. The physics reach of the experiment will also be presented.

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*Speaker

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1. Introduction

Reactors are a pure and intense source of $\overline{\nu}_e$ with energy lower than 10 MeV. They have been used during 1956 to assess the existence of the neutrino [1] and more recently to precisely measure the oscillation parameters Δm^2_{21} [2] and θ_{13} [3]. As pointed out in reference [4], reactors neutrinos can also be used to measure the mass hierarchy exploiting the interference between the "solar" and "atmospheric" oscillation amplitudes. With respect to other methods, e.g. ν_μ-disappearance and $\nu_\mu \rightarrow \nu_e$ long baseline experiments, the advantage is that the $\overline{\nu}_e$-disappearance probability is independent of θ_{23} and δ_{CP}, the less known oscillation parameters. An unprecedented detector energy resolution is however required.

Typical reactor $\overline{\nu}_e$ detectors employ Liquid Scintillator (LS) as target and sensitive medium. Antineutrinos interact mostly through Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$. IBD events are characterized by a prompt energy deposition, given by the positron ionization energy loss and annihilation ($E_{prompt} \simeq E_{\overline{\nu}_e}$ - 0.8 MeV), followed, after thermalization in times of several hundreds of μs, by the neutron capture on protons with the release of a 2.2 MeV γ. In case of small size, ton-scale detectors, the liquid scintillator is usually doped with gadolinium, for a faster thermalization (in times of tens of μs) and a neutron capture with the emission of γs for a total of 8 MeV. The delayed coincidence technique is at the base of IBD events selection; isotopes produced by cosmic ray interactions on ^{12}C, such as ^{9}Li and ^{8}Be, can mimic the signal because their β decays occur with the emission of a neutron. Their rejection is based on vetoing detector volumes around reconstructed cosmic ray tracks.

JUNO (JiangMen Underground Neutrino Observatory) in the GuangDong province of P. R. China has been designed primarily for such a measurement. It is located at an average distance of 52.5 km from the eight cores of two nuclear power plants (Yangjiang and Taishan) for a total thermal power of 26.6 GW.

2. JUNO experiment design and installation status

JUNO [5] [6] has been designed to measure the neutrino mass hierarchy, collecting about 10^5 IBD events in six years of data taking with 20 kt mass of liquid scintillator. The ambitious goal of 3% energy resolution at 1 MeV energy requires good liquid scintillator transparency over tens of meter distances and a photo coverage greater than 75%, obtained by means of 20" photomultipliers (LPMTs) with Photon Detection Efficiency (PDE) greater than 27%. The expected light yield is 1345 photo-electrons/MeV [6]. An energy scale uncertainty lower than 1% is obtained by means of a dedicated calibration system [7] and stereo-calorimetry with smaller PMTs (SPMTs). Another important feature is the radioactivity control of the detector components, whose strategy is described in [8]. A sketch of the detector, located in an underground laboratory under a 700 m overburden, can be found in figure 1.

The liquid scintillator used in the experiment is composed by LAB, Linear Alkyl Benzene, as base, with the addition of PPO, p-phenylphenoxazole, and bis-MSB, Bis(2-

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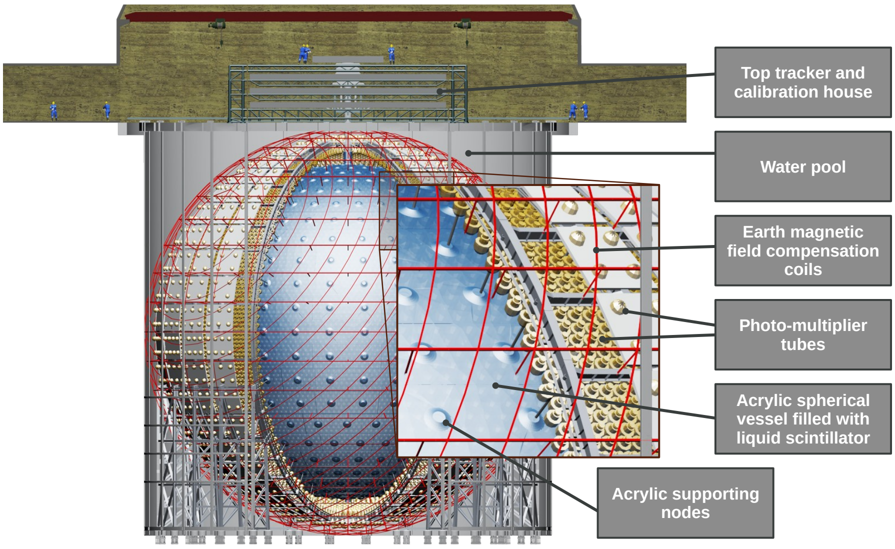

Figure 1: JUNO detector sketch.

methylstyryl)benzene, in concentrations of 2.5 g/l and 3 mg/l respectively [9]. In order to measure the neutrino mass hierarchy, contaminations lower than 10^{-15} g/g for $^{238}U/^{232}Th$, 10^{-16} g/g for ^{40}K and 10^{-22} g/g for ^{210}Pb are needed. To measure the flux of low energy solar neutrinos (from ^{7}Be and pep reactions) purity levels two orders of magnitude better are required. The purification is performed in multiple steps: in the external laboratory LAB passes through an Al_2O_3 filtration column (for improvement of optical properties) and a distillation tower (to remove heavy elements and improve the transparency); it is then mixed with the PPO and the bis-MSB. Underground the liquid scintillator undergoes water extraction (for removal of U/Th/K radioisotopes) and steam or nitrogen stripping (for removal of gaseous impurities like Ar,Kr,Rn). The liquid scintillator mixing system is fully commissioned and the start of detector filling is foreseen in 2024.

To measure the purity exploiting fast coincidences in the U/Th chains, a specific detector, called OSIRIS, using 17 t of liquid scintillator has been also installed in the underground laboratory [10]; its description is shown in figure 2 together with its picture.

The scintillator is enclosed inside an acrylic vessel, made by bulk polymerization of 265 panels, 12 cm thick, for a total weight of about 600 t. The acrylic transparency is required to be greater than 96% with high radiopurity (U/Th/K contamination lower than 1 ppt). The sphere is held by the Stainless Steel Structure (SSS) by means of supporting bars. The SSS and the acrylic vessel, filled with the LS, constitute the Central Detector (CD), which is immersed in a water pool. Pictures of the SSS and of the acrylic vessel installation are shown in figure 3.

The SSS holds also the PMT read-out systems. The light produced inside the LS is collected by means of more than 17612 20" PMTs, 5000 of which are R12860 dynode PMTs by Hamamatsu and the rest are produced by North Night Vision Technology (NNVT) company and based on Micro-Channel Plate (MCP) electron multiplication. Additional

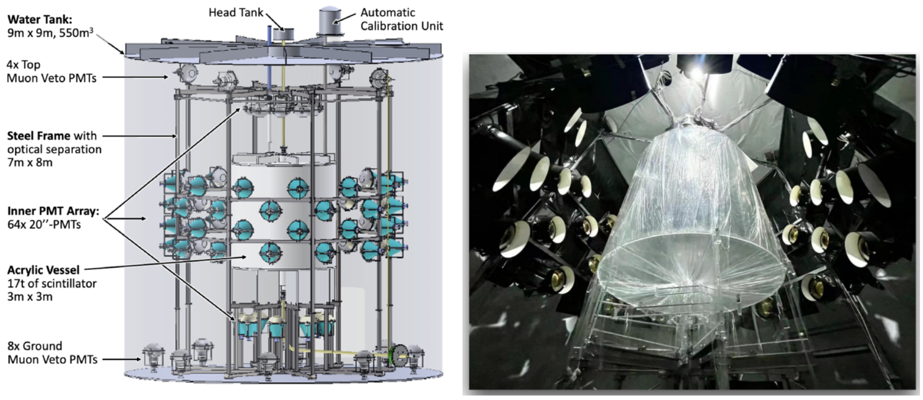

Figure 2: OSIRIS description (left) and picture (right).

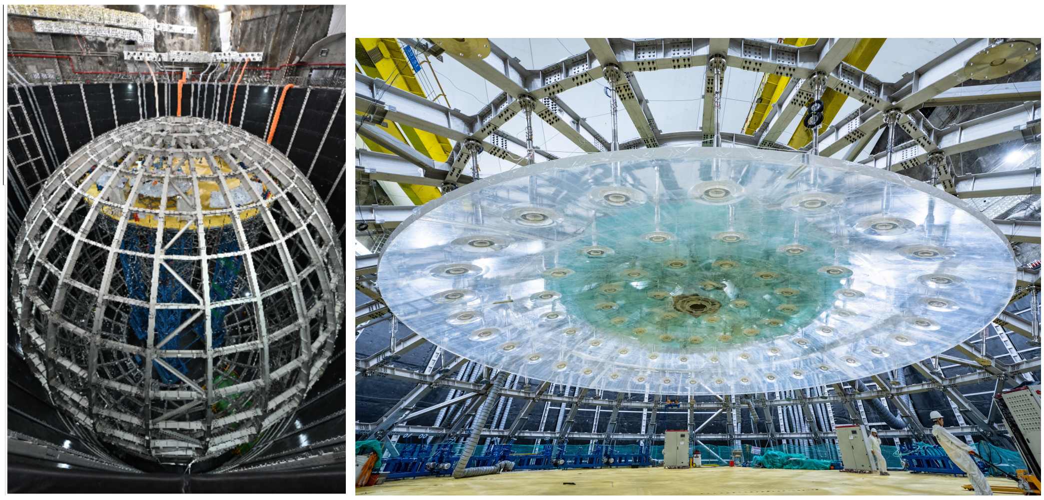

Figure 3: Stainless Steel Structure picture with inside the lifting platform for acrylic vessel installation (left). Picture of the acrylic vessel top pole installation (right).

2400 20" MCP PMTs are faced towards the water pool and used for collecting Cherenkov light. The PMTs are waterproof potted with the voltage divider and have anti-implosion protection.

All the produced LPMTs have been qualified in a dedicated facility located in Zhong-Shan by measuring their operating voltage, dark count rate (DCR), Transit Time Spread (TTS) and PDE [11]. In figure 4 the distributions of the measured PDE and DCR are shown. MCP PMTs have a slightly higher PDE with respect to Hamamatsu dynode PMTs at a price of a worse TTS (1.3 ns for the dynode PMTs versus 7 ns for the MCP ones). The average PDE greater than 27% matches the requirements. MCP PMTs because of their higher PDE are more suited for energy measurement, while the dynode ones are crucial for tracking and vertex reconstruction, their disposition having been optimized by means of a dedicated MonteCarlo simulation.

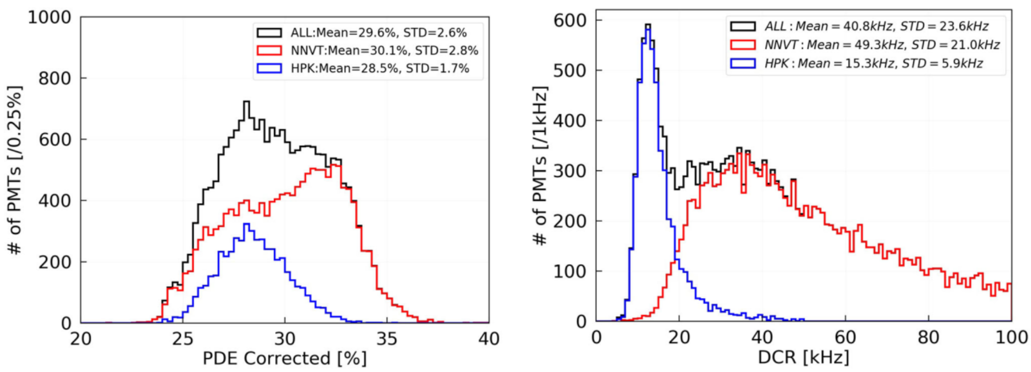

Figure 4: PDE (left) and DCR (right) measured over the whole LPMT production.

Each PMT is powered by one DC-DC converter and its signal is digitized at 14 bit by a custom ADC with 1 Gs/s sampling frequency. The converters and the ADCs of three PMTs are placed inside underwater boxes, containing also a dedicated 2 GB RAM memory for SuperNova events and driven by a FPGA based Global Control Unit. The trigger system (with a fixed latency of 2 μs) and the white rabbit [12] for synchronization are located in the electronics rooms outside of the water pool, connected to the underwater boxes through up-to 80 m long cables. A scheme of the read-out is shown in figure 5. More informations on the system can be found in [13] and [14].

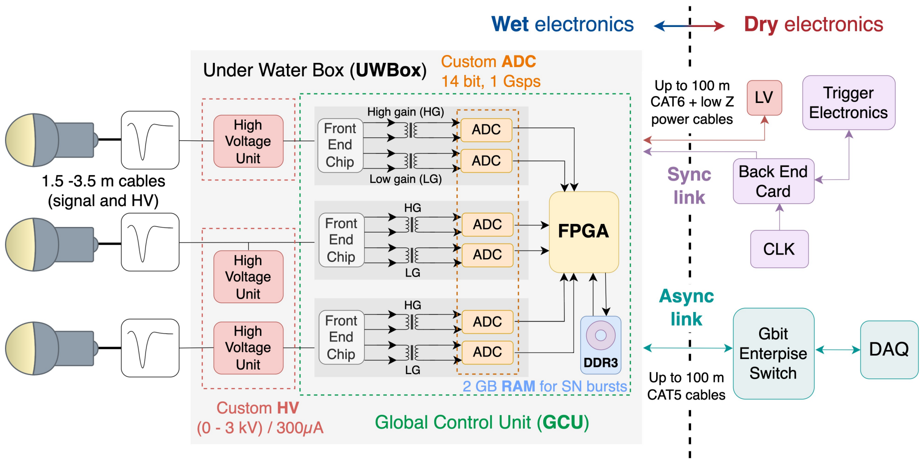

Figure 5: LPMT read-out system scheme.

The total photo coverage of the LPMTs is 75% and reaches 78% with the SPMT system. It is conceived similarly to the LPMT one, with 128 PMTs connected to an underwater box. The 25600 PMTs have been produced and tested by HZC company [15]. The Front-End electronics is based on the use of the CatiROC chip by weeroc [16]. The SPMT system is used as a complementary photo-detection system to improve the control of systematics and increase the dynamic range in photon-counting mode.

As of the end of November 2023, the acrylic sphere is almost completed and the installation of the electronics proceeds in coordination with that of the photomultipliers. At present about 30% of LPMT and SPMT systems is completed. A picture of the SSS with the photomultipliers and the electronics installed is shown in figure 6. As the installation proceeds, noise test campaigns are performed on the electronics; an average noise level of few ADC counts, about 4% (5%) of the single photo-electron amplitude for LPMTs (SPMTs) has been measured, well within specifications.

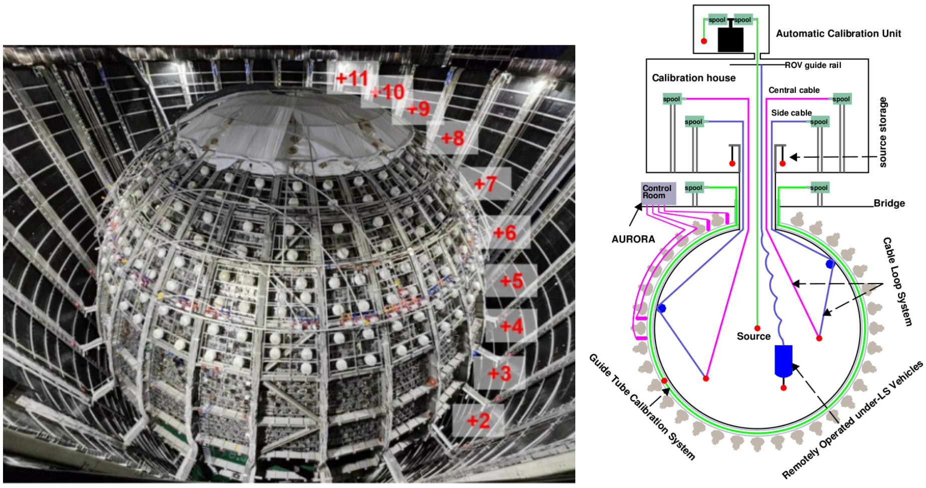

Figure 6: Picture of the SSS with the electronics and photomultipliers installed (left). Sketch of JUNO calibration system (right).

A systematic error lower than 1% is obtained by means of the SPMTs and of the calibration system, whose sketch is shown in figure 6. It is composed by four different subsystems employing γ, β and neutron sources:

- Automatic Calibration Unit (ACU): deploying sources in one dimension along the vertical axis.
- Cable Loop System (CLS): deploying sources in a 2D plane inside the acrylic vessel.
- Guide Tube (GT): running in a 2D plane in the inner surface of the vessel.
- Remotely Operated Vehicle (ROV): transporting sources in any position internal to the vessel.

The non-linearity of the liquid scintillator response is tackled with the use of different sources, the non-linearity of the Front-End electronics with intensity tunable sources and the detector non-uniformity by positioning sources in different detector places.

The CD is surrounded by 35 kt of ultra-pure water, acting as a shielding against neutrons, produced by cosmic rays interaction in the surrounding rock, as well as a Cherenkov veto for cosmic rays (a tagging efficiency greater than 99% is required against cosmogenic backgrounds). The Cherenkov light is collected by means of 2400 PMTs, installed on the

SSS and instrumented similarly to those for LS light read-out. The water is refilled and kept at 21 ^{o}C degree (with 1 degree tolerance) to avoid mechanical stresses to the Central Detector and to cool read-out electronics. In the SSS and in the water pool walls, Helmotz coils are placed in order to compensate the Earth magnetic field to avoid PMT performance deterioration [17].

As shown in figure 7, the water pool is covered by a Top Tracker of area 21×40 m^2 made by three layers of plastic scintillator strips, 2.6 cm wide and 6.86 m long. The light from the strips is collected by means of WLS fibers and read-out by means of 992 H7546 Multi anode PMTs by Hamamatsu. The Front-End electronics is based on MAROC3 chip by weeroc and realized in collaboration with CAEN. The full description of the system and of its electronics is reported in [18].

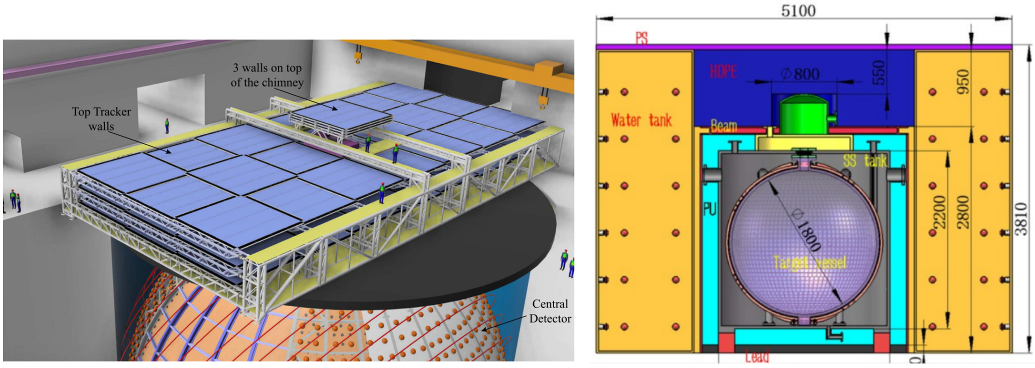

Figure 7: JUNO calibration system (left plot). TAO detector sketch (right plot).

The collaboration will also build, at a distance of about 30 from one of the cores, a reference detector, called TAO (Taishan Antineutrino Observatory) [19], in order to provide a a model-independent reference spectrum for JUNO and to investigate about antineutrino production models in reactors. A sketch of TAO detector is shown in figure 7. The detector is composed by 2.8 t of liquid scintillator enclosed in an acrylic vessel, surrounded by a water Cherenkov veto and a top plastic scintillator (PS) tagger. For an improved energy reconstruction with respect to JUNO, the light read-out will be based on a full coverage of SiPM tiles (with PDE $\sim$ 50%). To cope with the thermal noise of semiconductor devices, the liquid scintillator and the read-out electronics will be operated at -50 ^{o}C. The light yield of TAO detector will be about 4500 photo-electron/MeV, corresponding to an energy resolution better than 2% at 1 MeV.

3. JUNO physics reach

The JUNO experiment has been designed to reach at least 3 σ significance in the determination of the neutrino mass hierarchy [20] exploiting the interference between the "solar" and "atmospheric" oscillation amplitudes at the maximum of oscillations induced by the solar neutrino parameters. The 20 kt liquid scintillator detector, by means of suitable cuts for selection of IBD events and rejection of cosmogenic backgrounds, will detect, on the basis of an updated estimation, about 47 IBD/day with 4 background event/day. The reconstructed IBD energy spectrum expected in JUNO detector after 6 years of data taking is shown in figure 8, both for normal and inverse neutrino mass ordering. As also shown in figure 8, JUNO can determine the neutrino mass ordering with 3σ significance when normal ordering is true in 6.7 years of data taking; should inverse ordering be true, JUNO will reach 3.1 σ under the same exposure. According to [21] a 5 σ determination is possible in combination with ν_μ-disappearance data from PINGU, ORCA or Noνa and T2K in a time ranging from 2 to 7 years. Profiting of the large mass, JUNO will also determine Δm^2_{31}, Δm^2_{21} and $\sin^2(2\theta_{21})$ with sub-percent precision [22].

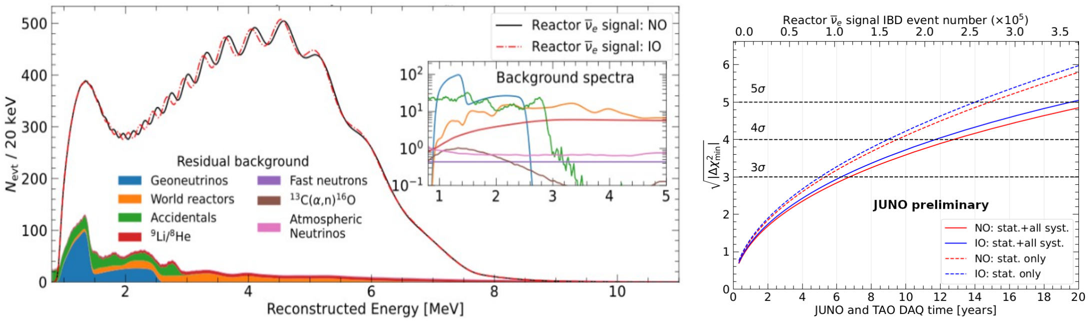

Figure 8: Reconstructed energy for IBD events in JUNO after 6 years of data taking, in case of both normal and inverse neutrino mass ordering (left plot). JUNO sensitivity to neutrino mass ordering as a function of JUNO and TAO data taking time (right plot).

The experiment will also measure solar neutrinos from the ^{8}B branch [23], performing an independent measurement of the solar neutrino oscillation parameters. Solar neutrinos from ^{7}Be and pep branches will also be measurable, depending on the reached purification level of the scintillator [24]. JUNO, with 20 kton scintillator mass, will also be a neutrino observatory from other natural sources (geo-neutrinos, super-nova [25] and atmospheric neutrinos [26]).

The experiment is also sensitive to the proton decay through the channel $p \to K^+\overline{\nu}$. Exploiting the threefold delayed coincidence $K^+ \to \mu^+ \to e^+$ to reject the atmospheric neutrino background, a limit of 9.6 $\times 10^{33}$ years at 90% CL can be reached after 10 years of data taking [27].

4. Conclusions

Reactor neutrino experiments played a key role in neutrino oscillation physics by measuring Δm^2_{21} and θ_{13}. In the near future electron antineutrino disappearance will also be used to determine the neutrino mass hierarchy.

JUNO will be the largest reactor antineutrino detector ever built (20 kton of liquid scintillator) with an unprecedented energy resolution (3% at E=1 MeV). Located at about 50 km from two nuclear power plants with a total power of 26.6 GWth, the experiment has been designed to reach in six years of data taking a 3 σ sensitivity on the neutrino mass hierarchy. At the same time, it will also measure other oscillation parameters with sub-% precision (θ_{12}, Δm^2_{21} and Δm^2_{31}) as well as neutrinos from natural sources. Beyond the Standard Model processes, like the proton decay, will also be investigated.

The detector installation proceeds quickly. As of the end of November 2023, the liquid scintillator mixing system is commissioned and the acrylic sphere almost completed. The installation of the photomultipliers and of their read-out systems is at about 30% of its completion, with encouraging results on the electronic noise measured on the apparatus. The start of detector filling is expected during 2024.

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