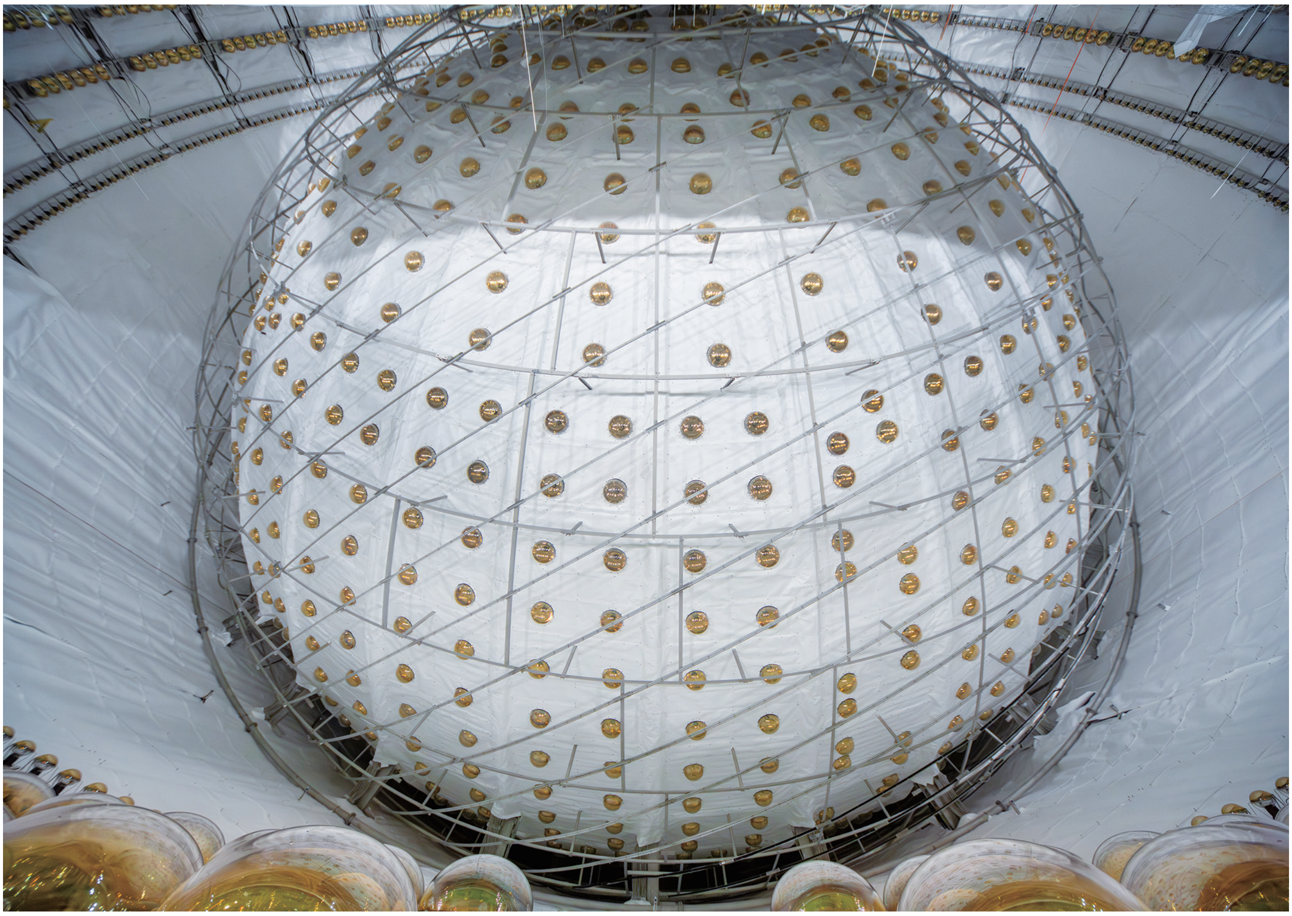
JUNO Formally Comes into Operation

By SONG Jianlan

This colossal instrument is set to determine the mass ordering of neutrinos—whether or not one type of neutrinos is heavier than another, and more.



The central detector, a liquid-scintillator detector, of the Jiangmen Underground Neutrino Observatory (JUNO) as seen from the outside. (Credit: JUNO Collaboration)

A well-anticipated neutrino observatory, the Jiangmen Underground Neutrino Observatory (JUNO) has now successfully completed all its civil construction as well as instrument installation and calibration to formally come into operation. On August 26, its central instrument, the liquid scintillator detector immersed in a pool of ultra-pure water, together with its water Cerenkov detector and top tracker, was officially switched on to start collecting data. This mega-science instrument now marks the first of the new generation of large-scale neutrino experiments to come into operation.

"For the first time, we have in operation a detector of this scale and precision dedicated to neutrinos. JUNO will allow us to answer fundamental questions about the nature of matter and the universe," says Prof. WANG Yifang, Member of the Chinese Academy of Sciences (CAS) and former Director of the CAS Institute of High Energy Physics (IHEP), which hosts the JUNO experiment. WANG serves as the spokesperson for JUNO.

The Quest for Neutrino Mass Hierarchy

Neutrinos are a family of building blocks that constitute the matter world. According to the Standard Model, matter consists of 12 types of elementary particles, of which six fall into quarks, three into charged leptons, and three into neutrinos. Neutrinos are ubiquitous: it is estimated that there are as many as about 300 neutrinos in every cubic centimeter of space in the universe, mostly legacy from the Big Bang. Many particle physics and nuclear physics processes can produce neutrinos, ranging from nuclear fission (e.g. nuclear power generation), nuclear fusion (hence can be found in the sunshine), natural radioactivity (e.g. beta decay), and supernova explosions, etc. However, neutrinos are the least known by human beings among elementary particles. They carry no electric charge, and bear very little mass, hence can easily penetrate normal matter with very little interaction with it. This makes it very hard to observe and investigate them. For example, when penetrating the Earth, a spheroid of over 12 thousand kilometers in diameter, only one out of every ten billion neutrinos would interact with the matter it bumps into, leaving behind almost no trail throughout its trajectory.

Among the many open questions about neutrinos is their mass hierarchy: Which of the three types of them is heavier? Which is the heaviest?

JUNO is designed to answer this question. Situated 729 meters underground near Jiangmen city in Guangdong Province of southern China, its detector will intercept the antineutrinos released from two nearby nuclear power plants, and measure their spectrum with record precision. With the two nuclear power plants respectively located in Taishan and Yangjiang cities about 53 kilometers away, the detector falls in an optimized distance to measure the spectrum at an ideal sensitivity. It will also closely observe the oscillation (or mixing)—the conversion from one type to another—of neutrinos, accurately measuring 3 of its 6 parameters. With data accumulating, scientists will be able to determine the mass hierarchy of neutrinos from the measured spectrum.

In contrast to other experiments, JUNO's approach to determining the mass hierarchy of neutrinos is independent of the matter effects from the Earth and largely free from parameter degeneracies, and hence will improve the measuring precision of several parameters of neutrino oscillation by orders of magnitude, according to IHEP. On the other hand, the JUNO experiment will also detect and investigate neutrinos of other sources, like supernovae, the Sun, the atmosphere, the Earth, and so on. Moreover, it will search for sterile neutrinos and proton decay, which are also on the fascinating frontiers of particle physics.

To precisely measure the spectrum and the oscillation parameters, a massive set of observational data is required; given the extremely low occurrence rate of interactions between the incoming neutrinos and the liquid scintillator in the detector, it is expected that a few years of operation is needed to obtain the first key results.

But it is a worthy cause. The mass hierarchy of neutrinos pertains to many fundamental issues, including those in astrophysics, astro-particle physics and other aspects of theoretical and experimental particle physics linked to the cosmic evolution. Therefore, answering this question will help scientists pursue some long-pending open questions. As a probe for stellar activities as well as the Earth's interior structure, neutrinos can also facilitate the studies on a series of astrophysical issues, such as the Earth's geophysics model and mechanism of supernova explosions, hence might help verify some theoretical models in geophysics and solar physics.

The JUNO Instruments

To reduce disturbance from cosmic rays as much as possible, the experiment hall is built 729 meters underground. Central to the hall is the liquid-scintillator detector housed in a cylindrical water pool of 44 meters deep. The major part of the detector is an acrylic ball of 35.4 meters in diameter. When filled with liquid scintillator, the whole acrylic sphere will measure about 20,000 tons in mass, reaching an unprecedentedly large effective mass to ensure the designed observational sensitivity. The water pool is filled with ultra-pure water.

Travelling across the pure water in the pool and penetrating the acrylic sphere, neutrinos will interact with the liquid scintillator inside to give off very dim flashes. These scintillation signals will be captured by the big array of photomultiplier tubes (PMTs) comprised of 17,612 20-inch PMTs installed on the surface of the acrylic sphere and 25,600 3-inch PMTs installed on the inner wall of the pool, and converted into electrical signals.

The pool, filled with ultra-pure water, will also work as a Cerenkov detector to record the Cerenkov light excited by cosmic rays—high-energy particles—bumping into the water. The PMTs around the pool will be used to detect and record the Cerenkov signals, and the 5,600-square-meter muon tracker installed on the top of the pool will also track and record trajectories of the cosmic rays. The data of the recorded Cerenkov signals, in combination with those of the trajectories of the cosmic rays, will help eliminate the cosmogenic background noises from the observational data.

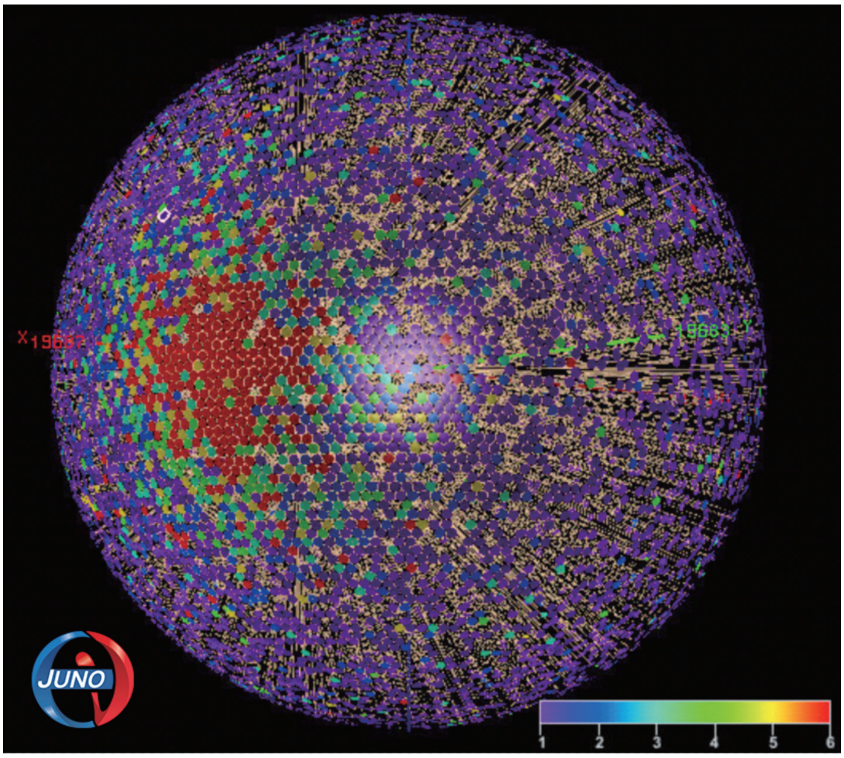
Meanwhile, the pool can also shelter the central detector from a large amount of natural radioactivity from the surrounding rocks and the secondary particles produced by cosmic rays.

Seen here is a patch of the acrylic sphere (bottom) of the central detector, and the surrounding photomultiplier tubes (the yellow, bubble-like "small balls"). Filling the acrylic sphere of a record size, the volume of the liquid scintillator is 20 times larger than the previously largest one in the world. (Credit: JUNO Collaboration)

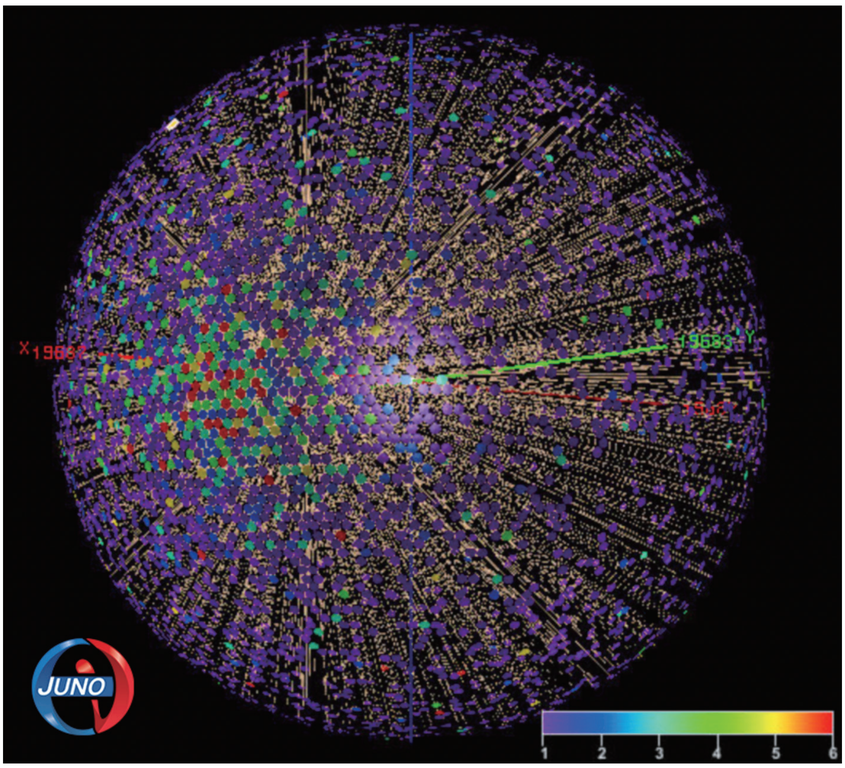
A Bold Design in Function

First initiated by IHEP in 2008, the project won support from CAS and also the local government of Guangdong Province in 2013. The construction of the tunnel and the underground experiment hall was launched in 2015 and completed in December 2021. The ensuing building and installation of the central detector were completed in December 2024, and subsequently the team started filling the pool and the acrylic sphere with ultra-pure water and liquid scintillator. Through refined and careful operation and adjustment, 20,000 tons of liquid scintillator was accurately filled in the acrylic sphere, maintaining a small level difference between the inner and outer layers through the process, so as to safeguard the structural integrity of the detector. Both the ultra-pure water and liquid scintillator are highly purified and transparent, with extremely low radioactive background, meeting the preset requirements for accurate observations.

"Building JUNO has been a journey of extraordinary challenges," comments Prof. MA Xiaoyan, Chief Engineer of JUNO. "It demanded not only new ideas and technologies, but also years of careful planning, testing, and perseverance. Meeting the stringent requirements of purity, stability, and safety called for the dedication of hundreds of engineers and technicians. Their teamwork and integrity turned a bold design into a functioning detector, ready now to open a new window on the neutrino world."



Prompt signal of a reactor neutrino event detected and recorded by JUNO on August 24, with energy of ~5.7 MeV. (Credit: JUNO Collaboration)



Delayed signal of a reactor neutrino event detected and recorded by JUNO on August 24, with energy of ~2.2 MeV. (Credit: JUNO Collaboration)

The JUNO experiment is now an international consortium led by IHEP, joining over 700 scientists from 74 institutions across 17 countries and regions. It is designed for a scientific lifetime of up to 30 years. In about 10 years from now, it is expected to be upgraded to perform the search for neutrinoless double-beta decay, a long-sought-after phenomenon in the cosmos. The search would help the humanity understand the absolute neutrino mass scale and test whether neutrinos are Majorana particles.

"The landmark achievement that we announce today is also a result of the fruitful international cooperation ensured by many research groups outside China, bringing to JUNO their expertise from previous liquid scintillator set-ups. The worldwide liquid scintillator community has pushed the technology to its ultimate frontier, opening the path towards the ambitious physics goals of the experiment," comments Prof. Gioacchino Ranucci, professor at the University of Milano and INFN-Milano and deputy spokesperson of JUNO.

Building on the success of the Daya Bay Experiment, JUNO is expected to open a new window onto the mysterious world of elementary particles. The determination of the neutrino mass hierarchy will have profound implications for research in the evolution of the universe; also, the precise measurements of the neutrino mixing parameters will make it possible for human beings to inspect the unitarity of the neutrino mixing matrix, which may lead to discoveries of new physics.