Jiangmen Underground Neutrino Observatory (JUNO) Experiment Postprint

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Abstract

Neutrinos are one of the most fundamental constituents of the material world. Compared with other fundamental particles (quarks and charged leptons), neutrinos possess special properties and are extremely difficult to detect; many fundamental scientific questions remain to be resolved. Research into the unknown aspects of neutrinos will not only refine our understanding of the most fundamental laws governing the material world, but may also reveal new physics beyond the existing Standard Model of particle physics.

Full Text

Preamble

Strategic Priority Research Program (Category A) of the Chinese Academy of Sciences
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Jiangmen Underground Neutrino Observatory (JUNO) Experiment

1. Background and Significance

Neutrinos are among the most fundamental building blocks of matter. Compared to other elementary particles (quarks and charged leptons), neutrinos possess unique properties and are extremely difficult to detect, leaving many fundamental scientific questions unresolved. Research into the unknown aspects of neutrinos will not only refine our understanding of the most basic laws of the physical world but may also reveal new physics beyond the Standard Model. Major scientific questions in this field include identifying the origins of ultra-high-energy cosmic rays, studying supernova explosion mechanisms, investigating solar models, using supernova background neutrinos to study large-scale cosmic structure, and employing geoneutrinos to study Earth' s evolution.

1.1 Frontiers of Neutrino Research

The discovery of atmospheric neutrino oscillations in 1998 and solar neutrino oscillations in 2002 indirectly demonstrated that neutrinos have tiny masses, representing the only experimental phenomenon beyond the Standard Model to date—research that was awarded the 2015 Nobel Prize in Physics. In 2012, the Daya Bay Reactor Neutrino Experiment discovered the third neutrino oscillation mode and measured the mixing angle 13. To date, four and a half of the six parameters describing neutrino oscillations have been measured, including three mixing angles (12, 23, and 13) and two mass-squared differences ($\Delta m^2{}_{21}$ and $|\Delta m^2{}_{32}|$). The unknown parameters include the sign of $\Delta m^2{}_{32}$ (known as the neutrino mass ordering) and the charge-parity (CP) phase angle.

The measurement of neutrino mass ordering represents the focal point of current neutrino research and holds major scientific significance. As an intrinsic property of neutrinos, mass ordering determines the flavor structure of neutrinos and must be addressed by all particle physics models. It directly affects neutrino-matter interactions and consequently plays a crucial role in cosmic evolution, the production and propagation of solar and supernova neutrinos, and various long-baseline neutrino oscillation phenomena. It also influences the experimental prospects for measuring the CP phase angle and determines the development direction of another important class of experiments—neutrinoless double-beta decay experiments.

Neutrino research has flourished in recent years, forming interdisciplinary connections with astronomy, cosmology, geophysics, and other fields. Neutrinos represent a new astronomical observation method with unique advantages for directly observing internal processes of celestial bodies.

1.2 Project Initiation

In 2008, the Institute of High Energy Physics of the Chinese Academy of Sciences proposed the concept of using reactor antineutrinos to measure the mass ordering. In 2013, this concept received support from the Strategic Priority Research Program of the Chinese Academy of Sciences, officially launching the Jiangmen Underground Neutrino Experiment (JUNO, originally named Daya Bay Phase II). Since the measurement of 13, the field has witnessed another round of intense international competition. JUNO is expected to be the first to determine the mass ordering, and due to its different experimental principle, its results can be cross-validated with accelerator-based and atmospheric neutrino experiments. The Chinese Academy of Sciences' support for JUNO through its Strategic Priority Research Program is crucial for winning this international competition and achieving major scientific breakthroughs first.

In addition to JUNO, seven other experiments internationally are at various stages of development (Table 1). Among these, NOvA has been constructed and is operational, but can only distinguish mass ordering when the CP phase angle equals 225–315 degrees. Other experiments each face their own technical challenges and require time to complete design and R&D, with expected start dates around 2020 (Table 1). These projected dates (marked with “~”) are for experiments not yet formally approved, with achievement timelines calculated at 3 standard deviations.

Table 1. Experimental programs for measuring neutrino mass ordering

Experiment	Type	Operation Start	Result Expected
US NOvA	Accelerator	2014	2020 (25% probability)
JUNO	Reactor	2020	2024
India INO	Atmospheric	2020	2030
US DUNE	Accelerator	2024	2027
France ORCA	Atmospheric	~2019	~2023
US Antarctic PINGU	Atmospheric	~2020	~2024
South Korea RENO-50	Reactor	~2020	~2024
Japan Hyper-K	Atmospheric	~2025	~2028

2. Originality and Innovation

(1) Experimental Concept. The JUNO concept, proposed by the Institute of High Energy Physics in 2008, represents the first international proposal to measure mass ordering using interference effects in reactor neutrino oscillations. The experimental design offers several key advantages: mass ordering measurement does not depend on the unknown leptonic CP phase angle, making it complementary to other experimental approaches; the effective reactor complex power is the highest in the world; and the experiment employs internationally leading liquid scintillator detector technology.

(2) Key Technologies. JUNO’ s detector effective mass is 20 times larger than KamLAND (currently the world’ s largest liquid scintillator detector), with designed energy precision improved by a factor of two compared to the internationally best-performing BOREXINO experiment—presenting enormous technical challenges. Building on Daya Bay’ s experience, the project team has mastered liquid scintillator technology featuring high transparency, high light yield, economic viability, and safety, as well as high-precision large-scale detector technology, reaching an internationally leading level. JUNO will adopt and further advance these key technologies.

(3) Novel Photomultiplier Tubes. The project has developed 20-inch photomultiplier tubes (PMTs) with the world’ s highest photon detection efficiency, meeting urgent needs for this project and other international neutrino experiments while breaking foreign monopolies and saving substantial research funds for China. This achievement has also driven development in domestic enterprises’ vacuum electronic device research, enhancing their technical capabilities and R&D capacity.

Since project implementation, the team has completed conceptual design and the physics goals white paper according to schedule. Supporting facility construction is underway, key technology R&D has achieved major breakthroughs, and primary technical challenges for reaching physics goals have been resolved. Main progress includes five aspects:

(1) **Management System and International Collaboration.** The project established a comprehensive organizational structure including a leading group, expert advisory committee, supervision group, overall management group, local work leadership group, project office, and 11 system-level teams. Management systems were perfected and a complete research team was established. An international collaboration group was formed with a management system conforming to international practices. The collaboration has grown from 12 countries/regions, 31 institutions, and 180 researchers in July 2014 to 15 countries/regions, 66 institutions, and 450 researchers (including approximately 200 from abroad). Each country’ s contributions and construction responsibilities have been clearly defined.

(2) **Physics Goals and Overall Experimental Design.** The “Physics White Paper” was published, establishing 11 research directions with defined objectives for each major scientific topic. For the most important physics goal–neutrino mass ordering–the experiment can achieve 3σ significance with a relative measurement method using 6 years of data, or 4σ with absolute measurement. The experiment will precisely measure sin\$^{2}2θ_{12}\$ and two mass-squared differences to better than 1% precision. Combined with Daya Bay’ s $_{13}$ measurement, JUNO will precisely measure four of the six neutrino oscillation parameters to the world’ s highest precision. Precise mixing parameter measurements will enable testing of mixing matrix unitarity and discovery of new physics. The conceptual design report was published, completing detector conceptual design and primary key technology R&D.

(3) **Detector Implementation Plan.** Design and prototype manufacturing of key components have been completed with international review. A small-scale detector model was built to study liquid scintillator and novel PMT performance. The detector comprises central and veto detectors. After comparing multiple options, the central detector adopted an acrylic sphere + stainless steel truss design (Figure 1 [Figure 1: see original paper]). The acrylic sphere has a diameter of 35.4 m and thickness of 12 cm, containing 20,000 tons of liquid scintillator and supported by 590 nodes on an outer stainless steel truss. Eighteen thousand 20-inch and 36,000 3-inch PMTs are mounted on the truss outside the acrylic sphere. The sphere and truss are immersed in a water pool 43.5 m in diameter and 44 m high containing 30,000 tons of pure water, optically separated into inner and outer layers at the truss. The inner layer forms the central detector for neutrino signals, while the outer layer is a water Cherenkov

detector with approximately 2,000 PMTs for cosmic ray detection. Plastic scintillator detectors are employed at the pool top as cosmic ray trackers.

(4) Novel Photomultiplier Tube Development. PMTs are vacuum devices that convert extremely weak light signals into electrical signals and represent a key experimental component. To achieve the required energy resolution, single-photon detection efficiency must exceed 27%. Previous commercial products could not meet this requirement, and relying on foreign development would incur prohibitive costs. To reduce experimental costs and drive domestic technological innovation, the Institute of High Energy Physics proposed a novel PMT design in 2009, using microchannel plates (leveraging domestic technical advantages) instead of traditional dynodes for multiplication, obtaining patents in multiple countries. Leading a consortium of seven organizations including North Night Vision Technology Co., Ltd. and Xi' an Institute of Optics and Precision Mechanics, the team successfully developed 20-inch MCP-PMTs with full intellectual property rights in 2015 (Figure 2 [Figure 2: see original paper]), achieving the world' s highest detection efficiency and winning the international bid for 15,000 units for this project. Compared to conventional dynode PMTs, MCP-PMTs feature high detection efficiency, high gain, low noise, good anode uniformity, fast response time, and high single-photon peak-to-valley ratio. Production line construction has been completed, with mass production beginning in 2017.

(5) High-Transparency Liquid Scintillator Development. Due to the detector' s enormous scale, liquid scintillator transparency is a critical factor, while natural radioactivity must be reduced to extremely low levels. The team studied purification methods including vacuum distillation, Al_2O_3 adsorption, water extraction, and steam stripping. The attenuation length of the primary raw material (alkylbenzene) exceeds 25 m, and the liquid scintillator attenuation length reaches over 20 m, representing the international highest standard. A medium-scale liquid scintillator purification system has been established at Daya Bay (Figure 3 [Figure 3: see original paper]) to purify and test 20 tons of liquid scintillator. Additionally, domestic development of fluor materials has succeeded, reaching international highest standards. The Rayleigh scattering length of alkylbenzene was measured for the first time to be 27 m. Large-scale production planning and design have been completed.

(6) Talent Development and Industrial Progress. JUNO has established an international collaboration group. Participation from numerous foreign scientists helps share construction and operation costs, expands international influence, and incorporates advanced foreign technologies and experience. Collaboration among scientists with different cultural backgrounds and research experiences fosters innovation, while the environment of international cooperation and competition helps cultivate domestic graduate students to international standards.

The project attaches great importance to talent cultivation and team building. The young and mid-career team trained through Daya Bay forms the main force of this project, with capabilities honed and tested in Daya Bay’ s international environment. Team members received the Young Scientist Award from the International Union of Pure and Applied Physics in 2016. The “Particle Physics Frontier Excellence Innovation Center” supported by this project selects three top young talents and 24 outstanding young researchers annually, providing substantial rewards to help retain and motivate excellent young researchers.

Internationally leading particle physics experiments often place high demands on industry. This project is domestically based and initiated key technology R&D early. Various task groups have worked closely with dozens of domestic enterprises, achieving major results. The successful implementation of the JUNO pilot project marks a new development stage for China’ s neutrino research, which will not only advance China’ s particle physics detector technology and promote major scientific discoveries but also establish an internationally leading research team, placing China’ s particle physics research at the forefront of the world while enhancing the technological innovation and international competitiveness of domestic related enterprises, making important contributions to the strategy of building China into a science and technology powerhouse.

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International Scientific Endorsements

Statement by Takaaki Kajita

Over the past two decades, extremely important progress has occurred in neutrino physics. In 1998, we learned that neutrinos change their flavor (or type) during long-distance propagation—phenomena known as “neutrino oscillations.” Neutrino oscillations occur if neutrinos have mass and non-zero mixing angles. Then in 2001 and 2002, we understood that the long-standing “solar neutrino problem” was also due to neutrino oscillations. In 2011-2012, the third oscillation mode was discovered, with China’ s Daya Bay experiment being a key contributor.

Based on these results, we almost understand the basic structure of neutrino masses (or more accurately, “mass differences”). However, one important piece remains missing: we do not know which of the three neutrino mass states is the heaviest (the mass hierarchy problem). This is a very important question to resolve experimentally. Depending on the true answer, our view of the physics that generates neutrino masses may be very different. Therefore, the neutrino community has discussed many possible experiments that could answer this question. One of the most promising is the Jiangmen Underground Neutrino Experiment, which will observe electron antineutrinos from the Yangjiang and Taishan nuclear power plants. Depending on the mass hierarchy pattern, the signals observed by JUNO will differ, thus enabling JUNO to determine the mass hierarchy. As described above, determining the mass hierarchy will be extremely important for neutrino physics and particle physics.

Through neutrino oscillation studies, we have learned that neutrino mixing angles are very different from quarks. This difference is very meaningful. Therefore, we believe that neutrino oscillation parameters, including mixing angles, should be measured as precisely as possible. JUNO is a unique experiment capable of measuring some of these parameters with the highest precision.

We know these experiments are very challenging. Particularly, determining neutrino mass hierarchy using this method is challenging because it requires very strict energy precision. However, the JUNO collaboration has done excellent work and sought various knowledge and expertise from the international neutrino community to meet these requirements.

Finally, in neutrino physics and other related scientific fields, we believe every experiment should be based on international cooperation to produce the best possible scientific results through discussion among people with different backgrounds and cultures. JUNO is located in China, but the collaboration is truly international. JUNO clearly meets global standards.

In summary, I believe JUNO is a very important experiment for the future of the global neutrino community.

Takaaki Kajita
Professor at University of Tokyo, Director of Institute for Cosmic Ray Research (ICRR). Awarded 2015 Nobel Prize in Physics with Arthur Bruce McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

Statement by Arthur Bruce McDonald

The Jiangmen Underground Neutrino Experiment (JUNO) will determine a very basic and important unknown quantity about neutrinos—the mass ordering of the three neutrino masses, known as the mass hierarchy. JUNO will achieve this goal by utilizing a carefully designed detector located near two high-power nuclear reactor complexes. This huge detector will also advance several other neutrino physics research areas, such as measuring neutrinos from the Sun, Earth, and reactors. JUNO will also provide higher precision for other neutrino parameters, which is very important for modifying the Standard Model of particle physics to accommodate massive neutrinos.

If the current progress continues, the JUNO project has hope of becoming the international leader in measuring neutrino mass hierarchy. The project leaders have established a large international collaboration of experienced scientists, and the project design is progressing very well. The Daya Bay neutrino experiment determined very important properties about mixing between the 1st and 3rd mass neutrinos, and through this excellent measurement, China has assumed a leadership position in neutrino physics. Based on this major result, the Daya Bay neutrino experiment team and Wang Yifang were awarded the prestigious 2016 Breakthrough Prize in Fundamental Physics. The technology and experience developed in Daya Bay form the core of JUNO and are being enhanced by more collaborators and further technology and experience in this larger experiment.

Recently, several of my Canadian colleagues participated in the international review of the JUNO experiment (central detector), bringing technology and experience from the Sudbury Neutrino Observatory. They were very impressed by the professional technology and physics potential demonstrated by this experiment.

China can utilize the world-class scientific opportunity provided by two high-power nuclear plants and a nearby underground experimental site to complete an important particle physics measurement through the JUNO project. Wang Yifang has assembled an excellent international team led by China to build JUNO and conduct these measurements. I sincerely hope the JUNO project can receive your country' s support and use this excellent opportunity to once again lead the world in measuring fundamental properties of neutrinos.

Arthur Bruce McDonald
Director and Professor of Sudbury Neutrino Observatory, Canada. Awarded 2015 Nobel Prize in Physics with Takaaki Kajita "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

Note: Figure translations are in progress. See original paper for figures.

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