Solar, supernova, atmospheric and geo neutrino studies using JUNO detector postprint

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Abstract

Aside from its primary purpose of shedding light on the mass hierarchy (MH) using reactor antineutrinos,the JUNO experiment in Jiangmen (China) will also contribute to study neutrinos from non-reactor sources. In this poster we review JUNO' s goals in the realms of supernova, atmospheric,solar and geo-neutrinos; present the related experimental issues and provide the current estimates of its potential. For a typical galactic SN at a distance of 10 kpc, JUNO will record about 5000 events from inverse beta decay, 2000 events from elastic neutrino-proton scattering, 300 events from neutrino-electron scattering, and the charged current and neutral current interactions on the 12C nuclei. For atmospheric neutrinos, JUNO should be able to detect ne and nm charged current events. Optimistically, a determination of the MH could be achieved at the 1.8s (2.6s) level after 10 (20) years of data taking. JUNO will also study solar neutrinos from 7Be and 8B, at low (1 MeV) and higher energies respectively, to improve our understanding of the matter effects on the oscillation mechanism and of the solar metallicity. Challenges come primarily from the radioactive and cosmogenic backgrounds: the expected performance for two benchmark scintillator radio-purities, are shown. The flux of geo-neutrinos gives us an insight on the Earth composition and formation. We will show how the increased sample size given by JUNO' s large sensitive mass of 20 KTon liquid scintillator will provide data to answer to several geological questions among which the U/Th ratio and mantle measurements

Full Text

Preamble

Solar, Supernova, Atmospheric and Geo-Neutrino Studies Using the JUNO Detector

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Beyond its primary mission of resolving the neutrino mass hierarchy (MH) using reactor antineutrinos, the Jiangmen Underground Neutrino Observatory (JUNO) experiment in China will also contribute significantly to neutrino studies from non-reactor sources. This poster reviews JUNO's scientific objectives in the domains of supernova, atmospheric, solar, and geo-neutrinos; discusses the relevant experimental challenges; and provides current estimates of its detection potential. For a typical galactic supernova at a distance of 10 kpc, JUNO will record approximately 5,000 events from inverse beta decay, 2,000 events from elastic neutrino-proton scattering, 300 events from neutrino-electron scattering, and additional events from charged-current and neutral-current interactions on 12C nuclei. For atmospheric neutrinos, JUNO should be capable of detecting e and charged-current events. Optimistically, the MH could be determined at the 1.8 (2.6) level after 10 (20) years of data collection. JUNO will also measure solar neutrinos from 7Be and 8B at low (1 MeV) and higher energies, respectively, to improve our understanding of matter effects on neutrino oscillations and solar metallicity. The primary challenges arise from radioactive and cosmogenic backgrounds; the expected performance for two benchmark scintillator radio-purity levels is presented. The flux of geo-neutrinos provides insight into Earth' s composition and formation, and JUNO' s large 20-kiloton liquid scintillator mass will yield a substantially increased sample size to address several geological questions, including the U/Th ratio and mantle measurements.

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1. Introduction

The JUNO experiment, described in [?], is a neutrino observatory under construction in China. Its primary scientific goal is to determine the neutrino mass hierarchy and precisely measure oscillation parameters using reactor antineutrinos. Achieving these objectives requires unprecedented energy resolution for reactor-produced $\bar{\nu}_e$, with a target resolution of 3% at 1 MeV. These stringent performance requirements also render JUNO well-suited for studying neutrinos from other astrophysical and geophysical sources, including the Sun, Earth' s interior, the atmosphere, and supernova explosions. Each of these topics carries significant implications for astrophysics or geophysics. The poster presented at the conference described JUNO' s potential to detect and measure the key parameters associated with these diverse neutrino sources.

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2. Atmospheric Neutrinos

The JUNO central detector features a very low energy threshold and excellent energy resolution for atmospheric neutrino measurements. Characteristic signatures from Michel electrons, neutron captures, and unstable daughter nuclei facilitate particle identification. The JUNO liquid scintillator (LS) detector also possesses directional reconstruction capabilities for charged leptons through the timing pattern of first-hit photomultiplier tubes (PMTs) [?]. Conservatively, only atmospheric ν_μ charged-current (CC) events with muon track length $L_\mu > 5$ m are considered for mass hierarchy extraction. For selected events, the final-state muon is assumed to be fully reconstructible and identifiable, with corresponding visible energy and muon angular resolutions of $\sigma_{E_{\rm vis}} = 0.01\sqrt{E_{\rm vis}/\rm GeV}$ and 1°, respectively.

Events are categorized into four classes based on muon track length and statistical $\nu/\bar{\nu}$ separation [?]. A 0.9 MH sensitivity can be achieved with 10 years of data for $\sin^2\theta_{23} = 0.5$, as shown in the left panel of Fig. 1 [Figure 1: see original paper]. The inverted hierarchy case yields similar results [?]. An optimistic scenario for neutrino mass hierarchy sensitivity is also considered. First, $\nu_e/\bar{\nu}_e$ CC events can be identified and reconstructed effectively when the $e^\pm$ visible energy fraction $E_e^{\rm vis}/E_{\rm vis} > 0.5$. Second, a less stringent requirement of $L_\mu > 3$ m is applied. Finally, the charged lepton direction is replaced by the full neutrino direction, with a 10° angular resolution. As shown in the right panel of Fig. 1, the combined sensitivity can reach 1.8 for $E_{\rm vis} > 1$ GeV and $E_e^{\rm vis} > 0.5$ with 10 years of data [?].

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3. Solar Neutrinos

The Sun is a powerful source of electron neutrinos with energies of order 1 MeV, produced through thermonuclear fusion reactions in the solar core (the pp chain and CNO cycle). The relative contributions of these processes can be used to infer stellar properties; in the Sun, the pp chain accounts for approximately 99% of the neutrino flux, comprising ν_e from pp, pep, hep, ^{7}Be, and ^{8}B reactions. The experimental signature consists of single electrons elastically scattered by incoming solar neutrinos. Studying the solar neutrino flux and energy spectrum enables investigation of important physics questions, such as testing the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect [?, ?] in particle physics, particularly in the energy region sensitive to new physics contributions ($E_\nu \approx 2-5$ MeV [?]), and verifying agreement between solar models and helioseismology data [?]. Thanks to its large exposure and excellent energy resolution, JUNO can compete with recent leading experiments in the field (e.g., [?]). It can contribute to measuring the ^{7}Be neutrino flux and discriminating pp neutrinos from the sharply decreasing ^{14}C spectrum. The primary challenges arise from backgrounds: intrinsic radioactivity from elements decaying in the liquid scintillator, acrylic vessel, and instrumentation; and cosmogenic isotopes produced by cosmic-ray muons interacting with ^{12}C, such as the long-lived ^{11}C and ^{10}C. The latter are particularly relevant for pep and ^{8}B/CNO solar neutrinos, respectively. The assumed baseline (ideal) radio-purity after liquid scintillator purification corresponds to a signal-to-background ratio S:B 1:3 (2:1). The resulting background and signal energy spectra for the baseline case are shown in Figure 2 [Figure 2: see original paper].

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4. Supernova Neutrinos

A massive star exceeding eight solar masses is expected to undergo core collapse under its own gravity, triggering a violent explosion in which 99% of the gravitational binding energy is carried away by an intense burst of neutrinos [?]. Measuring the neutrino burst from the next nearby supernova is a primary objective for both neutrino physics and astrophysics. As the largest liquid scintillator detector of the new generation, JUNO will be superior in terms of high statistics, excellent energy resolution, and rich neutrino flavor information [?]. For a Galactic supernova burst at 10 kpc, JUNO will register approximately 5,000 events from inverse beta decay (IBD), $\bar{\nu}_e + p \to n + e^+$, about 1,000 events from all-flavor elastic neutrino-proton scattering, $\nu + p \to \nu + p$, more than 300 events from neutrino-electron scattering, $\nu + e^- \to \nu + e^-$, as well as charged-current and neutral-current interactions on ^{12}C nuclei. Table 1 presents the expected neutrino event rates at JUNO for a supernova at a typical distance of 10 kpc. With these supernova neutrino measurements, JUNO may provide crucial information for determining the initial supernova neutrino fluxes [?], constraining the neutrino mass scale and ordering [?], testing collective neutrino oscillation scenarios, and even probing neutrino electromagnetic properties [?].

Table 1 : Numbers of neutrino events in JUNO for a SN at a typical distance of 10 kpc. Three representative values of the average neutrino energy $\langle E_\nu \rangle = 12$ MeV, 14 MeV and 16 MeV are taken for illustration. For the elastic neutrino-proton scattering, a threshold of 0.2 MeV for the proton recoil energy is chosen.

Channel	$\langle E_\nu \rangle = 12$ MeV	$\langle E_\nu \rangle = 14$ MeV	$\langle E_\nu \rangle = 16$ MeV
$\bar{\nu}_e + p \to n + e^+$ (IBD)	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$ (elastic)	0.6×10^3	1.2×10^3	2.0×10^3
$\nu_e + e^- \to \nu_e + e^-$	3.6×10^2	3.6×10^2	3.6×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	1.7×10^2	3.2×10^2	5.2×10^2
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	0.5×10^2	0.9×10^2	1.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	0.6×10^2	1.1×10^2	1.6×10^2

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5. Geo-Neutrinos

Geo-neutrinos are electron antineutrinos emitted by -decaying nuclei within the Earth. Those from thorium and uranium have the highest energies and are detected via inverse beta decay (IBD) in the JUNO liquid scintillator. The geo-neutrino flux at any location on Earth depends on the abundance and distribution of radioactive elements inside our planet. This flux has been successfully measured by the 1-kton KamLAND and 0.3-kton Borexino detectors, though these measurements are limited by low statistics. With its substantially larger mass, JUNO will collect sufficient data to separate the thorium and uranium contributions. The measured Th/U ratio can resolve several major questions in Earth science, including the sources of power driving plate tectonics, mantle convection, and the geodynamo, as well as the structure of mantle convection. The primary background for geo-neutrino studies originates from nearby nuclear power plants. Figure 2 shows the expected energy spectra for the geo-neutrino signal, reactor antineutrino background, and non-antineutrino backgrounds. Both scenarios with the Th/U ratio fixed to the chondritic value and with a free Th/U ratio have been considered. With 1, 3, 5, and 10 years of data, the precision of the geo-neutrino measurement with a fixed chondritic Th/U ratio is 13%, 8%, 6%, and 5%, respectively, improving with higher statistics as expected. Future work requires predicting the geo-neutrino flux at the JUNO experimental site. Geological, geophysical, and geochemical data will be integrated into a three-dimensional reference model of the lithosphere [**?**], after which geologists and particle physicists will collaborate to calculate the regional geo-neutrino flux.

6. Conclusions

The poster presented illustrates the anticipated potential of the JUNO experiment for measuring properties of neutrinos from the Sun, Earth, and astrophysical events. The main background sources and selection strategies have been described. Thanks to its enormous exposure and expected unprecedented energy resolution, JUNO should be highly competitive and improve upon previous measurements, with unique capabilities for, e.g., supernova neutrino detection.

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