PROCEEDINGS OF SCIENCE

Geoneutrino physics at JUNO

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Geoneutrinos are produced by radioactive decays of long-lived isotopes, such as uranium, thorium, and potassium, within the Earth. Consequently, the geoneutrino flux depends on the abundance and distribution of these radioactive elements throughout the planet. By measuring this flux, we gain critical information not only for particle physics but also for geology, as geoneutrinos provide a unique tool to investigate the Earth's radiogenic power and composition. To date, two experiments, KamLAND (Kamioka Liquid Scintillator Antineutrino Detector) and Borexino, have successfully detected geoneutrinos. The Jiangmen Underground Neutrino Observatory (JUNO), currently under construction in southern China, represents a next-generation experiment. With its large volume and high-precision measurement capabilities, JUNO will enable unprecedented measurements of the geoneutrino flux. This work presents the predicted geoneutrino signal at JUNO and evaluates its sensitivity to the total geoneutrino flux.

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1. Introduction

The Earth's structure is composed of distinct layers: the core, which forms the innermost region; the mantle, the intermediate layer; and the crust, the outermost layer. Understanding the internal heat sources and the convective heat transfer within these layers is essential for comprehending the Earth's surface heat flux. The cooling processes of the core and mantle are predominantly governed by convective heat transfer, with radioactive elements — known as Heat Producing Elements (HPE), particularly potassium, thorium, and uranium — contributing significantly to the surface heat flow. Geoneutrinos, which are (anti)neutrinos produced by the decay of long-lived isotopes such as those of the HPE, provide a powerful tool for understanding the distribution of these elements within the Earth.

Particle physicists have successfully detected the Earth's geoneutrino flux, produced by the decay of ^{238}U e ^{232}Th, using the inverse beta decay (IBD) reaction. The first detection of these particles was achieved in 2005 by the KamLAND experiment, a 1-kiloton liquid scintillator (LS) detector located in Japan [1]. Over 18 years of measurements, the KamLAND collaboration reported the detection of 174^{+31}_{-29} or 183^{+29}_{-23} geoneutrinos, depending on the fit procedure used [2]. In 2010, the Borexino collaboration reported the detection of $9.9^{+14.6}_{-8.2}$ geoneutrino events with a 99.73% confidence level (CL) [3]. Using a detector containing 252.6 tons of LS and after collecting data over 3262.74 days, the Borexino experiment, located at the Laboratori Nazionali del Gran Sasso, Italy, reported a total detection of $52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geoneutrinos [4].

High-precision geoneutrino measurements from particle physics are essential for advancing geoscientific research. With its large 20 ktons LS volume, located 650 meters underground, the JUNO detector will annually collect a significant number of geoneutrinos [5–7]. Equipped with over 17,000 20-inch Large Photomultiplier Tubes (LPMT) and more than 25,000 3-inch Small Photomultiplier Tubes (SPMT), JUNO represents a groundbreaking advancement in electron antineutrino detection, offering an unprecedented energy resolution of 3% at 1 MeV. Furthermore, it is expected to determine the neutrino mass ordering with a significance of 3σ within approximately 6 years of data collection.

2. Signal prediction at JUNO

The radiogenic heat production within the Earth originates primarily from the radioactive decay of U, Th, and K. These processes release energy, as exemplified by the decay chains of the following isotopes:

$$
\begin{aligned}
{}^{238}_{92}\mathrm{U} &\rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV},\\
{}^{232}_{90}\mathrm{Th} &\rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.6522\,\mathrm{MeV},\\
{}^{40}_{19}\mathrm{K} &\rightarrow {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}.
\end{aligned}
$$

The $\bar{\nu}_e$ are detected via the IBD reaction: $\bar{\nu}_e + p \rightarrow e^- + n$, which has an energy threshold of 1.806 MeV. Consequently, geoneutrinos from ${}^{40}_{19}$K cannot be detected through this mechanism, as their energy is insufficient to trigger the IBD process. Given the abundances of U and Th, along with the mass of a specific layer within the Earth, the radiogenic heat production can be calculated, and the associated geoneutrino flux can be predicted.

Employing an existing Reference Earth Model (RM), the geoneutrino signal at JUNO was calculated in Ref. [8]. This model divides the silicate Earth into lithospheric and mantle reservoirs, providing estimates of the thorium and uranium abundances in each layer [9]. A total geoneutrino signal of $39^{+6.5}_{-5.2}$ TNU was obtained, where one Terrestrial Neutrino Unit (TNU) corresponds to one detected event per year in a detector containing 10^{32} free protons, assuming a detection efficiency of 100%. The uncertainty arises solely from the input parameters associated with the lithosphere.

The expected geoneutrino signal at JUNO was also calculated using a different model, JULOC-I. This advanced 3D crustal model incorporates seismic data, gravity measurements, rock sample analysis, and heat flow data to estimate the geoneutrino contribution from the lithosphere [10]. The study predicts a total geoneutrino signal of $49.9^{+4.64}_{-3.31}$ TNU.

2.1 Neutrino oscillations

JUNO is a multipurpose experiment, and in addition to geoneutrinos, it will detect a large number of reactor antineutrinos, which are also observed via the IBD reaction. Since JUNO is primarily sensitive to electron antineutrinos through the IBD process, it is crucial to consider the phenomenon of neutrino oscillations.

The rate and energy spectrum of the geoneutrino flux are influenced by the survival probability of electron antineutrinos, $\Phi(E_{\bar{\nu}_e}) \propto P_{ee}(E_{\bar{\nu}_e}, L)$. Consequently, the following oscillation parameters must be accounted for: $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, Δm^2_{21}, and Δm^2_{31}. It is important to note that although both geoneutrinos and reactor antineutrinos are affected by neutrino oscillations, the oscillation patterns differ. Reactor antineutrinos originate from a fixed baseline, while geoneutrinos have varying baselines, distributed across the Earth's interior.

2.2 Backgrounds

The primary background for geoneutrino measurements arises from reactor antineutrinos. Within the energy range of geoneutrinos, it is not feasible to differentiate individual events between reactor antineutrinos and geoneutrinos. Non-antineutrino backgrounds must also be carefully evaluated, as their signals can mimic the IBD reaction within the detector. These backgrounds arise from various sources, such as cosmic muons, spallation products, and natural radioactivity in the surrounding environment or detector materials. The number of events, as well as the rate and shape uncertainties for geoneutrinos and the primary background sources, are summarized in the table below (1). Adjacent to the table, the energy spectra are displayed, showing geoneutrinos, reactor antineutrinos and other non-antineutrino backgrounds [6]. It is worth noting that JUNO will detect more geoneutrinos in one year than KamLAND and Borexino have ever detected combined.

3. JUNO's sensitivity to geoneutrinos

It can be observed from Figure (1) that one of the major challenges for JUNO is to extract the geoneutrino signal from the high reactor antineutrino background. To analyze the sensitivity of JUNO to the geoneutrino flux, a standard least-squares method was employed. Detailed calculations can be found in [6]. With a fixed Th/U ratio set at 3.9, the precision of the geoneutrino measurement is 13% for one year of data taking and 5% for ten years. JUNO can also estimate the contributions

Source	Events/year	Rate (%)	Shape (%)
Geoneutrino	408	NA	NA
Reactor	16100	2.8	1
$^{9}\mathrm{Li} - ^{8}\mathrm{He}$	657	20	10
Fast neutrons	36.5	100	20
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	18.2	50	50
Accidental	401	1	-

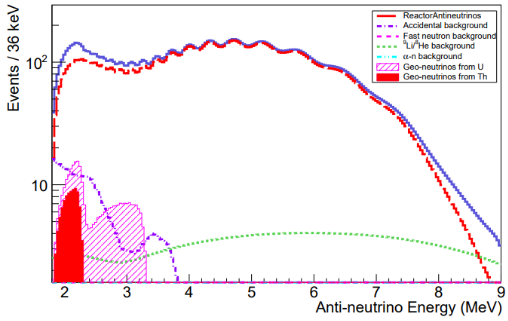

Figure 1: Left: Event numbers per year, rate and shape uncertainties for the energy range [1.8, 9.0] MeV. Right: Energy spectra of geoneutrinos, reactor antineutrinos, and other background sources at JUNO for one year of data collection.

of Th and U separately. In this case, the precision for Th is 80% for one year of data and 30% for ten years, while for U, the precision is 40% for one year and 15% for ten years.

4. Conclusion

Geoneutrinos offer a unique probe of the Earth's composition and structure. With just one year of data, JUNO will surpass all other experiments in terms of geoneutrino statistics, detecting more events than have been observed by any previous experiment. This unprecedented dataset will enable JUNO to achieve the highest precision in geoneutrino measurements. Additionally, JUNO will measure the individual contributions of uranium (U) and thorium (Th) with remarkable statistical significance. The data collected will provide a valuable opportunity to refine mantle models and further validate their accuracy.

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