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Search for neutron invisible decay modes in JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multipurpose underground Liquid Scintillator (LS) detector currently under construction in southern China. One of the capabilities of the JUNO detector is to search for the baryon number violation processes, which would be a crucial step towards testing the Grand Unified Theories and explaining the matter-antimatter asymmetry of the Universe. Nucleon decay provides a direct observation of baryon number violation and has been the focus of many experiments over the past several decades. The large LS detector of JUNO has a distinct advantage in detecting nucleon decay. The JUNO LS target consists of about 88% C (99% ^{12}C) and 12% ^{1}H. The invisible decays of neutrons from the s-shell in ^{12}C will result in a highly excited residual nucleus. It has been found that some de-excitation modes of the excited nucleus can produce time- and space-correlated triple signals. This talk reports the JUNO potential to search for invisible decay modes of the neutron. Based on MC simulations, we made comprehensive estimates for all possible backgrounds, including accidental triple coincidences from inverse beta decays, natural radioactivities and cosmogenic isotopes. The correlated backgrounds from atmospheric neutrino neutral current events have also been evaluated. We adopt the Pulse Shape Discrimination (PSD) and Multi-Variate-Analysis (MVA) techniques for suppressing backgrounds. A preliminary result to neutron invisible decays in JUNO will be presented.

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1. Introduction

The conservation of the baryon number B is an accidental symmetry in the Standard Model of particle physics, while the baryon number violation is one of three basic ingredients to generate the cosmological matter-antimatter asymmetry from an initially symmetrical Universe [1]. On the other hand, the baryon number B is necessarily violated in the Grand Unified Theories (GUTs) [2], which can unify the strong, weak and electromagnetic interactions into a single underlying force. However, no experimental evidence to date for the proton decay or B-violating neutron decay has been found. Discovering nucleon decay now remains as a key signature of grand unification. The neutron is hypothesized to have two invisible decay modes: $n \to inv$, $nn \to inv$. Currently the KamLAND experiment places the best limit $\tau(nn \to inv) > 1.4 \times 10^{30}$ yr [3]. For single neutron disappearance, the current best limit $\tau(n \to inv) > 9.0 \times 10^{29}$ yr comes from the SNO+ experiment [4], which is slightly higher than the KamLAND limit $\tau(n \to inv) > 5.8 \times 10^{29}$ yr [3]. Here we shall study invisible neutron decays with the JUNO detector.

2. Search for neutron invisible decay modes in JUNO

JUNO is an underground 20 kton Liquid Scintillator (LS) detector located in Southern China [5], with a 650-meter rock overburden for shielding against cosmic rays. As a multipurpose neutrino observatory, JUNO comprises the Central Detector (CD), Veto Detector, and Calibration System [6]. 17612 20-inch and 25600 3-inch photomultiplier tubes will be used in JUNO central detector for light detection, providing ~ 78% photon coverage. Together with a LS attenuation length greater than 20 m, JUNO expects a light yield of 1665 photoelectrons per MeV and an unprecedented energy resolution better than 3% at 1 MeV. The LS detectors have distinct advantages in the search for some nucleon decay modes, such as $p \to \bar{\nu} K^+$ [7] and the neutron invisible decays [3, 8].

2.1 Signal signature

JUNO LS includes about ~ 87% ^{12}C and 12% ^{1}H. The invisible decay of neutron from the s-shell in ^{12}C will lead to a highly excited residual nucleus. Then the excited nucleus can emit the secondary particles (p, n, α, γ) and leave a daughter nucleus. It is found that some de-excitation modes of the excited nucleus can give the time-, energy- and space-correlated triple signals in the LS detector. Here we consider the following four de-excitation modes from single and double neutron disappearances [8]:

$$
\begin{aligned}
{}^{11}\mathrm{C}^* &\to n + {}^{10}\mathrm{C} && (B_{n1} = 3.0\%), && (1)\\
{}^{11}\mathrm{C}^* &\to n + \gamma + {}^{10}\mathrm{C} && (B_{n2} = 2.8\%), && (2)\\
{}^{10}\mathrm{C}^* &\to n + {}^{9}\mathrm{C} && (B_{nn1} = 6.2\%), && (3)\\
{}^{10}\mathrm{C}^* &\to n + p + {}^{8}\mathrm{B} && (B_{nn2} = 6.0\%), && (4)
\end{aligned}
$$

where the three daughter nuclei from them ^{10}C (β^+, 19.3 s, 3.65 MeV), ^{9}C (β^+, 0.127 s, 16.5 MeV) and ^{8}B($\beta^+\alpha$, 0.770 s, 18.0 MeV) are radioactive. The corresponding decay mode, half-life and energy release have been indicated in brackets.

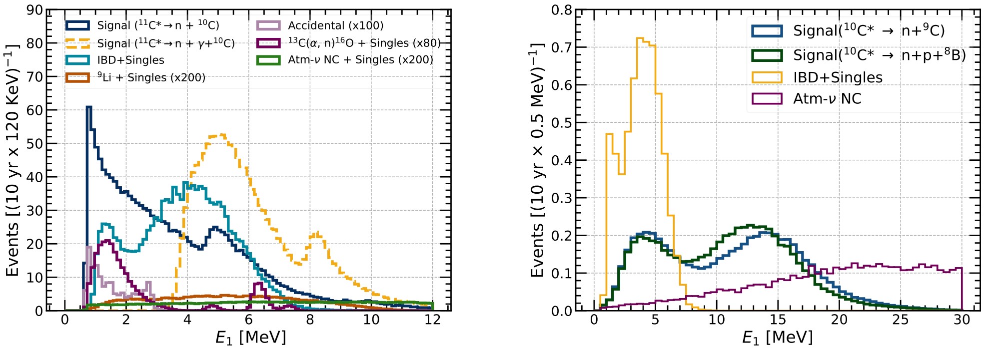

Figure 1: The prompt energy distributions of the triple coincident signals and dominant backgrounds from $^{11}\mathrm{C}^* \rightarrow n +^{10}\mathrm{C}$ (dash line) and $^{11}\mathrm{C}^* \rightarrow n + \gamma +^{10}\mathrm{C}$ (dashed line) in the $n \rightarrow inv$ analysis (left panel), $^{10}\mathrm{C}^* \rightarrow n +^{9}\mathrm{C}$ and $^{10}\mathrm{C}^* \rightarrow n + p +^{8}\mathrm{B}$ in the $nn \rightarrow inv$ analysis (right panel).

2.2 Background

As discussed in Sec. 2.1, the neutron invisible decays can generate a triple coincident signal in the LS detector. The main challenge is to distinguish these rare events from dominant backgrounds, which have been classified into six categories: the IBD (inverse beta decay) + Singles, Cosmogenic isotope (^{9}Li/^{8}He) + Singles, FN (fast neutrons) + Singles, ^{13}C(α,n)^{16}O + Singles, Accidental backgrounds and Atm-ν NC (atmospheric neutrino neutral current) events. Minimizing these backgrounds is essential for enhancing the sensitivity to rare decay processes.

2.3 Event selection

To enhance the JUNO potential on the neutron invisible decays, we should choose the proper event selection criteria to effectively suppress the backgrounds while keeping a high signal efficiency. In order to reduce the rate of long-lived cosmogenic isotopes, we design an effective muon veto strategy. The main targets of the muon veto strategy are to reject ^{9}Li/^{8}He and to remove some triply correlated events from three isotopes produced by the same muon as much as possible. These two veto strategies include whole detector veto after muon, cylindrical veto around the muon track and neutron-sphere veto (neutrons occurring within a specific time period post-muon). After event selection(energy, time and spatial selection), the results are shown in Fig. 1. For $n \rightarrow inv$ and $nn \rightarrow inv$, the signal efficiencies of $^{11}\mathrm{C}^* \rightarrow n +^{10}\mathrm{C}$, $^{11}\mathrm{C}^* \rightarrow n + \gamma +^{10}\mathrm{C}$, $^{10}\mathrm{C}^* \rightarrow n +^{9}\mathrm{C}$ and $^{10}\mathrm{C}^* \rightarrow n + p +^{8}\mathrm{B}$ are 35.6 ± 0.2 %, 43.6 ± 0.2 %, 53.9 ± 0.2 %, 49.1 ± 0.2 %, respectively. After the basic event selections, there are still a lot of backgrounds as shown in Fig. 1.

In order to reject these backgrounds further, additional suppression methods need to be considered. Based on the different profiles of time distributions between signals and backgrounds, we can use the pulse shape discrimination (PSD) technique to separate the neutron invisible decays from these backgrounds. The PSD separation capabilities are shown in Fig. 2. Furthermore the multivariate machine learning technique is widely used to distinguish signals from backgrounds in the field of experimental physics, which can combine multidimensional features of signals. The corresponding results of MVA testing are shown in Fig. 3. we have also employed the straightforward parameter of signal-to-noise ratio ($\epsilon_{sig}/\sqrt{N_{bkg}}$) to assess the performance of machine learning.

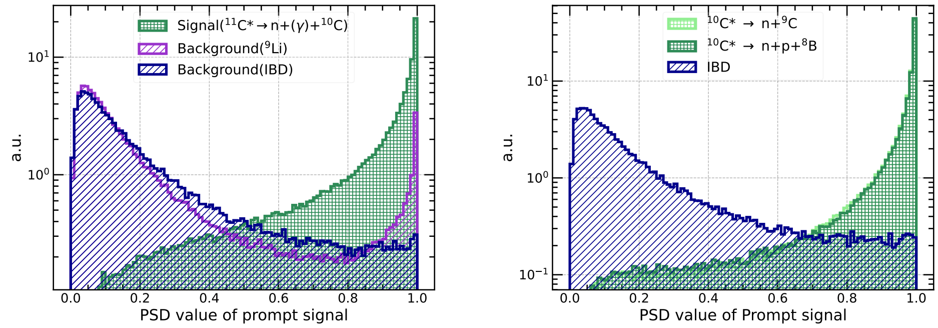

Figure 2: PSD separation capabilities for the $n \longrightarrow inv$ (left) and $nn \longrightarrow inv$ (right) modes.

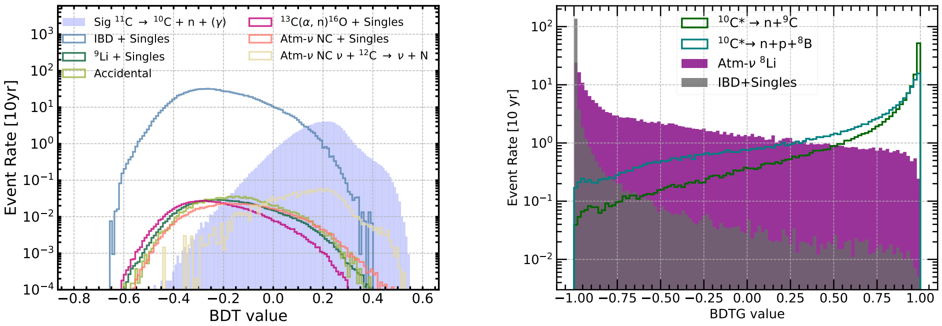

Figure 3: MVA outputs of $n \longrightarrow inv$ and $nn \longrightarrow inv$.

Before ML, the $\epsilon_{sig}/\sqrt{N}_{bkg}$ is ~ 0.01 ($n \longrightarrow inv$) and ~ 0.2 ($nn \longrightarrow inv$). After ML, there has been an improvement in the ratio value, which has been ~ 0.06 ($n \longrightarrow inv$) and ~ 0.6 ($nn \longrightarrow inv$). Predictably, machine learning can improve the sensitivity.

3. Summary

We have investigated the neutron invisible decays in the JUNO LS detector. The muon veto strategy and some basic selection criteria are applied. Simultaneously, we provide a detailed estimation of all potential background sources, as depicted in Fig. 1. It is found that the IBD+Singles is the dominant background. To suppress backgrounds further, we also employ the PSD and MVA techniques for the $n \longrightarrow inv$ and $nn \longrightarrow inv$ analyses. We compared the sensitivity metric $NBr\epsilon_{sig}/\sqrt{N}_{bkg}$, where N is the number (pair) of target neutrons, Br is the branching ratio, and ϵ_{sig} is the signal efficiency, across JUNO, KamLAND, and SNO+. Our analysis reveals that JUNO exhibits a higher sensitivity metric compared to KamLAND [3] and SNO+ [4]. This research displays JUNO's considerable potential for investigating invisible neutron decays.

References

[1] A. D. Sakharov, "Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe", Sov. Phys. Usp. **34**, 392 (1991).

[2] P. Nath and P. Fileviez Perez, "Proton stability in grand unified theories, in strings and in branes", Phys. Rept. **441**, 191-317 (2007).

[3] T. Araki *et al.* [KamLAND], "Search for the invisible decay of neutrons with KamLAND", Phys. Rev. Lett. **96**, 101802 (2006).

[4] A. Allega *et al.* [SNO+], "Improved search for invisible modes of nucleon decay in water with the SNO+ detector", Phys. Rev. D **105**, no.11, 112012 (2022).

[5] F. An *et al.* [JUNO], "Neutrino Physics with JUNO", J. Phys. G **43**, no.3, 030401 (2016).

[6] Z. Djurcic *et al.* [JUNO], "JUNO Conceptual Design Report", [arXiv:1508.07166 [physics.ins-det]].

[7] T. M. Undagoitia *et al.*, "Search for the proton decay p —> K+ anti-nu in the large liquid scintillator low energy neutrino astronomy detector LENA", Phys. Rev. D **72**, 075014 (2005).

[8] Y. A. Kamyshkov and E. Kolbe, "Signatures of nucleon disappearance in large underground detectors", Phys. Rev. D **67**, 076007 (2003).