PROCEEDINGS OF SCIENCE

# Nucleon decays at JUNO

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The Jiangmen Underground Neutrino Observatory (JUNO) is a large liquid scintillator detector designed to explore many topics in fundamental physics. 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. The large liquid scintillator detector of JUNO has distinct advantages in the search for some nucleon decay modes. This talk reports the JUNO potential to search for $p \to \bar{\nu} K^+$ and neutron invisible decays (e.g., $n \to 3\nu$ or $nn \to 2\nu$). Both of them can produce time-, energy- and space-correlated triple coincidence signals, which may be used to effectively suppress backgrounds. It has been found that the expected sensitivities for JUNO with 10 years of data are $\tau/B(p \to \bar{\nu} K^+) > 9.6 \times 10^{33}$ years, $\tau/B(n \to inv) > 5.0 \times 10^{31}$ years and $\tau/B(nn \to inv) > 1.4 \times 10^{32}$ years at the 90% confidence level, which are better than the current best limits.

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[*] Speaker

## 1. Introduction

Baryon number violation is one of three basic ingredients to generate the cosmological matter-antimatter asymmetry from an initially symmetrical universe [1]. Baryon number $B$ is necessarily violated, and the proton must decay 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 proton decay or $B$-violating neutron decay has been found [3]. Discovering nucleon decays plays a key role for understanding baryon asymmetry and test GUTs.

JUNO is a 20 kton multipurpose underground liquid scintillator (LS) detector under construction in China, with a 650-meter rock overburden (1800 m.w.e.) for shielding against cosmic rays [4–6]. Its central detector is a 12 cm thick acrylic sphere with a diameter of 35.4 m, filled with 20 kton LS. The JUNO LS detector has distinct advantages in the search for some nucleon decay modes [7, 8]. This talk will briefly report the JUNO expected sensitivities to $p \to \bar{\nu} K^+$ [7] and the neutron invisible decays [8].

## 2. JUNO sensitivity to $p \to \bar{\nu} K^+$

Among many possible nucleon decay modes, $p \to \bar{\nu} K^+$ is one of the two dominant decay modes predicted by a majority of GUTs. In the JUNO LS detector, the decay will give rise to a three-fold coincidence feature in time as shown in the left panel of Fig. 1, which is usually composed of a prompt signal by the energy deposit of $K^+$, a short-delayed signal ($\tau = 12.38$ ns) by the energy deposit of decay daughters of $K^+$ and a long-delayed signal ($\tau = 2.2\ \mu$s) by the energy deposit of the final Michel electron. The dominant background is caused by atmospheric neutrinos since the visible energy of $p \to \bar{\nu} K^+$ is mostly concentrated in the range of $200\,\text{MeV} \le E_{\text{vis}} \le 600\,\text{MeV}$ [7]. For atmospheric neutrino interactions, the pion production events with an energetic neutron, e.g. $\nu + p \to \nu + n + \pi^+$, can mimic the signature of $p \to \bar{\nu} K^+$. This is because that energetic neutrons have a small probability to propagate freely for more than 10 ns in the LS. In this case, the neutron interaction can cause a sufficiently large second pulse. In fact, $\bar{\nu}_\mu$ charged current quasi-elastic scattering $\bar{\nu}_\mu + p \to n + \mu^+$ can also contribute to this kind of background. The resonant and non-resonant kaon production (with or without $\Lambda$) have a negligible contribution in the relevant energy range.

To discriminate the $p \to \bar{\nu} K^+$ signals from the enormous amount of backgrounds, we design a series of selection criteria based on the simulation data sample. The basic event selection about the visible energy is firstly applied. Then we employ all delayed signals of $p \to \bar{\nu} K^+$ and atmospheric neutrino events, including the Michel electron and neutron capture. Besides the common cuts on energy, position and temporal features, additional criteria have to be explored since about 6.8% of the total atmospheric neutrino events would survive. The key part of the selections is based on the triple coincidence signature in hit time spectrum. We use the multi-pulse fitting method to reconstruct the time difference and energy of the $K^+$ and its decay daughters. After applying all criteria, the total efficiency for $p \to \bar{\nu} K^+$ is estimated to be 36.9%, while the expected background level corresponds to 0.2 events in 10 years. Thus, the JUNO sensitivity on $p \to \bar{\nu} K^+$ at the 90% confidence level with 200 kton-years would be $\tau / B(p \to \bar{\nu} K^+) > 9.6 \times 10^{33}$ years as shown in the right panel of Fig. 1 [7], which is higher than the current best limit of $5.9 \times 10^{33}$ years [3].

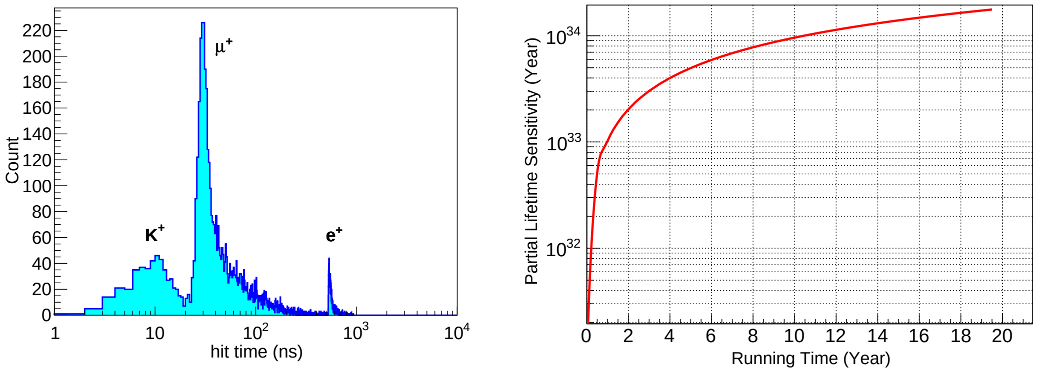

**Figure 1:** Left: illustration of the hit time spectrum of a typical $p \to \bar{\nu} K^+$ event, containing the signals of $K^+$, the decay daughter of $K^+$ ($\mu^+$ in this event) and the Michel electron; Right: the JUNO sensitivity for $p \to \bar{\nu} K^+$ as a function of running time at the 90% confidence level.

## 3. JUNO sensitivity to neutron invisible decays

The JUNO LS includes about 88% $^{12}$C and 12% $^{1}$H [4]. The invisible decays of neutrons from the $s$-shell in $^{12}$C will lead to a highly excited residual nucleus. Then the excited nucleus can emit secondary particles $(p, n, \alpha, \gamma)$ and leave a daughter nucleus. It has been found that four de-excitation modes of the excited nucleus can give time-, energy-, and space-correlated triple signals in the LS detector [9], as labeled in the left panel of Fig. 2. The first signal comes from neutron elastic and inelastic scatterings with free protons and $^{12}$C. The neutron will quickly slow down and be thermalized after many collisions. In the LS, these thermalized neutrons are captured by a free proton $\sim 220\,\mu$s later and give a second signal of the 2.2 MeV $\gamma$ ray. The third signal arises from the $\beta^+$ decay of the daughter nuclei $^{10}$C, $^{9}$C, and $^{8}$B. The dominant backgrounds can be classified into six categories [8]: IBD (inverse beta decay) + Single, Cosmogenic isotope ($^{9}$Li/$^{8}$He) + Single, FN (fast neutron) + Single, $^{13}$C($\alpha$,n)$^{16}$O + Single, Accidental backgrounds, and Atmospheric neutrino neutral current events, where “Single” means the events with no other correlated triggers and mainly originates from natural radioactivity and radioactive isotopes induced by cosmic muons.

To enhance JUNO’s sensitivities to the one and two neutron invisible decays, we design an effective muon veto strategy and choose proper event selection criteria (energy, time and spatial selection) to suppress backgrounds while maintaining the high signal efficiency. It is found that the signal efficiencies of $^{11}\mathrm{C}^* \to n + ^{10}\mathrm{C}$, $^{11}\mathrm{C}^* \to n + \gamma + ^{10}\mathrm{C}$, $^{10}\mathrm{C}^* \to n + ^{9}\mathrm{C}$, $^{10}\mathrm{C}^* \to n + p + ^{8}\mathrm{B}$ are 35.6%, 43.6%, 54.0%, 49.2%, respectively. However, there are still a lot of backgrounds. To suppress these backgrounds further, we employ pulse shape discrimination and multivariate analysis techniques in both searches. After 10 years of JUNO data taking, the expected background numbers for $n \to inv$ and $nn \to inv$ are $4.07 \pm 0.68$ and $0.69 \pm 0.64$, with final signal efficiencies of 26.7% and 42.3%, respectively. Therefore the JUNO expected sensitivities are $\tau/B(n \to inv) > 5.0 \times 10^{31}$ years and $\tau/B(nn \to inv) > 1.4 \times 10^{32}$ years at the 90% confidence level in 10 years [8]. As shown in the right panel of Fig. 2, JUNO will yield an improvement by an order of magnitude with respect to the current best limits after two years of data.

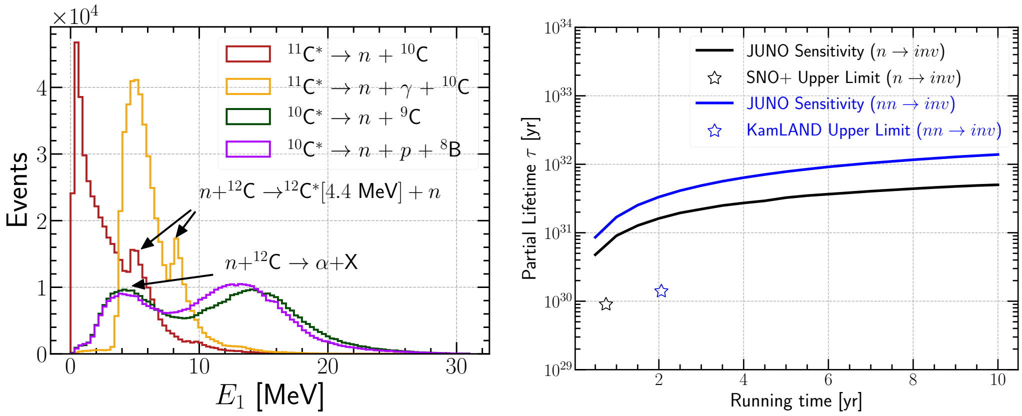

**Figure 2:** Left: the energy distributions of first signals from $^{11}\mathrm{C}^* \longrightarrow n +^{10}$ C and $^{11}\mathrm{C}^* \longrightarrow n + \gamma +^{10}$ C in the $n \longrightarrow inv$ case, $^{10}\mathrm{C}^* \longrightarrow n +^{9}$ C and $^{10}\mathrm{C}^* \longrightarrow n + p +^{8}$ B in the $nn \longrightarrow inv$ case; Right: the JUNO sensitivities to $n \longrightarrow inv$ and $nn \longrightarrow inv$ as a function of the running time at the 90% confidence level.

## 4. Summary

We have reported the JUNO expected sensitivities to $p \longrightarrow \bar{\nu} K^+$ and neutron invisible decays. The triple coincidence characteristics arising from them have been briefly described. Then we have discussed the corresponding backgrounds and the employed methods to select signals and reject backgrounds. Finally, the expected sensitivities for JUNO with 10 years of data are $\tau/B(p \longrightarrow \bar{\nu} K^+) > 9.6 \times 10^{33}$ years, $\tau/B(n \longrightarrow inv) > 5.0 \times 10^{31}$ years and $\tau/B(nn \longrightarrow inv) > 1.4 \times 10^{32}$ years at the 90% confidence level, which are better than the current best limits.

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