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Discovery potential for supernova relic neutrinos with slow liquid scintillator detectors

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ABSTRACT

Detection of supernova relic neutrinos could provide key support for our current understanding of stellar and cosmological evolution, and precise measurements of these neutrinos could yield novel insights into the universe. In this paper, we studied the detection potential of supernova relic neutrinos using linear alkyl benzene (LAB) as a slow liquid scintillator. The linear alkyl benzene features good separation of Cherenkov and scintillation lights, thereby providing a new route for particle identification. We further addressed key issues in current experiments, including (1) the charged current background of atmospheric neutrinos in water Cherenkov detectors and (2) the neutral current background of atmospheric neutrinos in typical liquid scintillator detectors. A kiloton-scale LAB detector at Jinping with $\mathcal{O}(10)$ years of data could discover supernova relic neutrinos with a sensitivity comparable to that of large-volume water Cherenkov detectors, typical liquid scintillator detectors, and liquid argon detectors.

1. Introduction

Galactic core-collapse supernovae are estimated to occur at a rate of only a few per century [1], and 99% of the gravitational binding energy of these events is carried away by neutrinos. Besides detection of neutrino bursts from explosion of a supernova, such as 1987A [2–7], detection of supernova relic neutrinos, SRNs, also known as the diffuse supernova neutrino background, DSNB, can also be expected. These neutrinos originate from an enormous number of supernova explosions throughout the time and space of the universe and can provide researchers with novel insights into stellar evolution and cosmology.

Current experimental upper limits were obtained from the SNO experiment in 2006 [8], the KamLAND experiment in 2012 [9], and the Super-Kamiokande (SK) experiments in 2012 [10] and 2015 [11]. Relatively low signal-to-background ratios are the main problem of these studies. In the future, gadolinium-doped water detectors [12–14], typical liquid scintillator detectors with the scintillation light pulse shape discrimination [15–18], or liquid argon time projection chamber detectors [19–21] may come online to improve findings in this filed of research.

Slow liquid scintillators feature scintillation emission time significantly longer than the Cherenkov emission time and may thus help identify different particles. Linear alkyl benzene (LAB) has been suggested to be a candidate target material in slow liquid scintillators for the future Jinping neutrino experiment [22] because it can be directly used or improved to increase light yield by mixing wave-length shifters. Using the results measured in Ref. [23], we studied the potential of using LAB as a realistic candidate target material to detect SRN.

This paper is organized as follows: We summarize the key issues and possible solutions of SRN detection in Section 2, present the ability of LAB in particle identification (PID) in Section 3, report the sensitivity of SRN detection with LAB at Jinping in Section 4, and then conclude our study in Section 5.

2. SRN detection

2.1. SRN signal

The differential SRN flux, $d\phi(E)/dE$, is calculated by integrating the rate of core-collapse supernovae, $R_{\text{ccSN}}(z)$, the energy spectrum of neutrino emission, dN/dE, and the redshift, z, over the cosmic time, [24]

$$\frac{d\phi(E)}{dE} = c\int R_{\text{ccSN}}(z)\frac{dN(E')}{dE'}(1+z)\left|\frac{dt}{dz}\right|dz \quad (1)$$

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where $|dz/dt| = H_0(1+z)[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$ and $E' = E(1+z)$. H_0, Ω_m, and Ω_Λ are cosmological parameters.

Many SRN models haven been constructed to predict both the flux and the spectrum. Earlier models were developed before SN1987A [25–27], and even more sophisticated models [28–34] were proposed after SN1987A. The shapes of the predicted SRN fluxes are similar among these models. In this paper, we adopted a recent HBD model described in Ref. [34] by Horiuchi, Beacom and Dwek. The effective neutrino temperature, 6 MeV, in the HBD model is used in this paper as a typical value.

2.2. Detection in hydrogen-rich detector

In a hydrogen-rich detector, supernova relic neutrinos and supernova burst neutrinos are primarily detected via inverse beta decay, IBD, $\bar{\nu}_e + p \to n + e^+$, due to their large cross section, which is about 2 orders of magnitude greater than the next most-frequent interaction channels [35], for instance, elastic scattering on electrons and charged/neutral current scattering on entire nuclei. Notice that in a liquid argon time projection chamber detector, LArTPC, SRN events are detected via the neutrino charged and neutral current interactions with argon nuclei as well as elastic scattering on argon electrons. In the case where energies are lower than $\sim$20 MeV, the dominant backgrounds for LArTPC in the SRN study come from ^{8}B and *hep* solar neutrinos [36]. Since LArTPC presents a fairly unique detection technique and background, as well as the heavy water Cherenkov detector such as SNO [8], this section focuses on the hydrogen-rich detector.

2.2.1. Detection techniques

Liquid scintillator (LS): A prompt-delayed coincident measurement of an IBD event is generally performed in LS, based on the scintillation photons emitted once a charged particle deposits energy in it. The prompt signal is from the deposited energy of the positron and its annihilation gammas. The delayed emission of gamma(s) is given by the neutron capture on hydrogen or doped isotopes (e.g., gadolinium (Gd)). The coincidence from the prompt and delayed signals provides a clear signature against the backgrounds from the accidentals, radioactivity, and other flavors of neutrinos with different interactions, for instance, solar neutrinos.

Water: A water Cherenkov detector identifies IBD events based on the Cherenkov photons radiated by the IBD positrons. In general, no prompt-delayed coincidence measurement is performed in the water Cherenkov detector, as the 2.2 MeV gamma obtained from neutron capture on hydrogen is difficult to detect (e.g., in the early stages of the SK experiment). A forced trigger could be implemented for the later stage of the SK data to search for a delayed coincident 2.2 MeV signal of neutron capture on hydrogen [11,13]. The neutron-tagging technique in water allows the powerful coincident measurement of an IBD event based on Cherenkov photons despite a low tagging efficiency.

Water doped with gadolinium (Gd-water): For water doped with Gd, the total energy of the emitted gammas from neutron capture on Gd is $\sim$8 MeV, which enables distinct neutron tagging in comparison with the 2.2 MeV gamma from neutron capture on hydrogen. A high neutron tagging efficiency of about 90% can be obtained with a 0.2% of $GdCl_3$-water solution [13].

2.2.2. Background mechanism

The key backgrounds for SRN detection in current hydrogen-rich detectors are basically categorized into three types: the cosmic-ray muon-induced background, the reactor neutrino background, and the charged and neutral current backgrounds induced by atmospheric neutrinos.

Cosmic-ray muon-induced backgrounds: An energetic cosmic-ray muon interacting with a carbon (oxygen) nucleus can produce a radioactive spallation background that can mimic an SRN signal [37]. This background dominates the SRN analysis in water Cherenkov detectors and can be significantly suppressed by the neutron-tagging technique; an exception to this finding involves the ^{9}Li/^{8}He background, which has the exact same signature of an IBD event. The ^{9}Li/^{8}He background can also affect the studies in liquid scintillator detectors. The cosmic-ray muon-induced fast neutron is a typical background in liquid scintillator detectors. Neutrons could migrate into the detector and recoil protons or inelastically scatter with carbon nuclei, promptly producing a scintillation signal followed by neutron capture mimicking an IBD event.

Reactor neutrino background: The $\bar{\nu}_e$'s from nuclear power plants are an indistinguishable background for the SRN search. The energy of reactor neutrinos can be as high as $\sim$10 MeV [38,39].

Atmospheric neutrino background: The atmospheric neutrino background originates from the four flavors of atmospheric neutrinos, i.e., $\bar{\nu}_e$, ν_e, $\bar{\nu}_\mu$, and ν_μ [40].

For charged current interactions with protons or carbon (oxygen) in a detector,

- The atmospheric $\bar{\nu}_e$'s form an intrinsic background for the SRN study and are irreducible. Due to the indistinguishable reactor neutrino flux and the atmospheric $\bar{\nu}_e$ flux, a golden window for the SRN study is defined within about 8–30 MeV of neutrino energy [12].
- The atmospheric ν_e CC background can be ignored, particularly with the neutron-tagging technique, as the cross sections of various types of atmospheric ν_e CC interactions with protons or carbon (oxygen) are about two orders of magnitude smaller than the $\bar{\nu}_e$ IBD interaction in the golden window of neutrino energy for the SRN study; the flux is fairly similar to the atmospheric $\bar{\nu}_e$ flux in this energy range.
- The atmospheric $\bar{\nu}_\mu/\nu_\mu$ CC interaction always produces a muon and, in most cases, a neutron even for the ν_μ. The muon can decay into a final state with an electron. These particles would produce Cherenkov lights and probably mimic an IBD event, thereby contaminating the selected IBD sample. The $\bar{\nu}_\mu/\nu_\mu$ CC interaction has a relatively high energy threshold equal to roughly the mass of a muon (105.7 MeV).

For the neutral current interactions of all the flavors of atmospheric neutrinos, $\pi^\pm$ or π^0 would be produced, and this promptly decays into a final state with a muon or two gammas. An energetic neutron can be produced in some cases, recoiling protons or inelastically scattering with carbon (oxygen) nuclei in the detector. Some isotopes could also be induced with emission of deexcitation gammas. These particles/processes could contaminate the selected IBD sample and produce a main background for the SRN study, particularly in the scintillator detector.

A compilation of different atmospheric neutrino backgrounds and detection techniques is given in Section 2.3.

2.3. Issues and possible solutions

The backgrounds induced by cosmic-ray muons and reactor neutrinos are basically crucial for the searches of low-energy SRN events, which relies on the rock overburden and the conditions of the nuclear power plants surrounding the detector.

The comparative advantages and key issues presented by different SRN detection techniques are presented in Table 1 in terms of the atmospheric neutrino backgrounds excluding the intrinsic at-