PROCEEDINGS OF SCIENCE

Sources of background and veto strategies for background mitigation in the JUNO experiment

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The Jiangmen Underground Neutrino Observatory, is a multipurpose neutrino experiment located at 53 km from the Yangjiang and Taishan nuclear power plants in south-east China. Its main purpose is determining the neutrino mass ordering using precision spectral measurement of the reactor neutrino signal. The detector is composed of a 20 kiloton spherical liquid scintillator (LS) volume seen by 17612 20" photomultiplier tubes (PMT) and 25600 3" PMTs. The LS volume is enclosed in a water Cerenkov veto filled with 34 kton of ultrapure water seen by 2400 20" PMTs. A muon tracker composed of 3 layers of plastic scintillator strips surmounts the LS volume. The neutrino detection is done through inverse beta decay (IBD) resulting in a two-fold signal given by the positron and the neutron capture on H after ~200s. Various processes can mimic IBD, hence contributing to the background in the detector: natural radioactivity, cosmogenic isotopes, fast neutrons and (α,n) reactions are the major backgrounds of the reactor neutrino signal. A set of cuts including fiducial volume, energy, PSD, time-position correlation of the prompt and delayed signal helps to mitigate accidentals and (α,n) backgrounds. To reject the cosmogenics induced by muons with a rate of ~4Hz, muon veto cuts are necessary: an optimized volume around the muon track or cosmic-induced neutron is vetoed. In the following, we'll present the backgrounds to the neutrino signal and the veto strategies to mitigate these backgrounds.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

*Speaker

PoS(TAUP2023)191

1. Experimental site and detector design

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose experiment under construction in Southeast China. Its main goal is to determine the neutrino mass ordering (NMO). To this end, it will study the oscillation pattern of antineutrinos emitted by the reactor core of two nuclear power plants located at 50 km from the detector. In addition to the determination of the NMO, the JUNO experiment will be able to significantly improve the precision of $\sin^2\theta_{12}$ and Δm^2_{31}, Δm^2_{32}, Δm^2_{21} [1]. The detector is located at 53 km from the nuclear power plants of Yangjiang and Taishan, to benefit from the oscillation maximum, hence optimising the sensitivity to the mass ordering. Installed in an underground laboratory with an overburden of ~650 m (~2000 m.w.e), the detector is composed of a Central Detector (CD): a 20 kton liquid scintillator target (LS) inside a 35.4 m diameter acrylic sphere, the LS is seen by 17 612 20-inch PMTs and 25 600 3-inch PMTs attaining an energy resolution of 2.95 $\%/\sqrt{E}$. Surrounding the CD a Water Cherenkov Detector (WCD) in the form of a 43.5 × 44 m cylinder filled with 35 ktons of ultrapure water and seen by 2400 20-inch PMTs acts as passive shielding against natural radioactivity from surrounding rock and fast neutrons, tagging muon with a detection efficiency of 99.5 %. Finally, the whole assembly is surmounted by a 3 layers plastic scintillator Top Tracker (TT) with a 2.6×2.6 cm^2 granularity, it shows a muon track angular resolution of 0.2°.

2. Neutrino signal and background

The reactor antineutrino constitutes the signal for the determination of the neutrino mass ordering and the precision measurement of the oscillation parameters.They are detected by inverse beta decay process (IBD): $\bar{\nu_e} + p \rightarrow e^+ + n$. The IBD process produces a twofold signal: a prompt signal from the positron ionising the medium and then annihilating with an electron; a delayed signal from the neutron capture on H resulting in a 2.2 MeV gamma. The antineutrino energy is directly related to the positron energy: $E_{\bar{\nu}} = E_{e^+} + 0.8$ MeV. The space-time correlation of the IBD prompt and delayed signals provides a clear signature, allowing for background discrimination. Nevertheless, several sources of background were identified: accidentals, cosmogenics, fast neutrons, carbon induced correlated events, geo-neutrinos, world reactors, atmospheric neutrinos (see Figure 1). A set of selection cuts covering: fiducial volume (FV), visible energy range, IBD's space-time correlation and a muon veto strategy, was optimised to reduce the various background described hereafter. The detail of each cut can be found in [2].

2.1 Accidental background

The rate of accidental background is given by: $R_{acc} = R_p \times R_d \times \Delta t_{p-d}$, where R_p and R_d are the rate of prompts and delays respectively, and Δt_{p-d} is the coincidence time window. The accidental background consists of three types of coincidence:

(radioactivity, radioactivity): The rate of singles estimated from MC simulation is 7.6 Hz with ~8% of neutron like signals. Hence, the rate of prompt-delayed coincidence within 1.0 ms is ~410/day. A cut, consisting in requiring a distance between prompt and delayed vertex below 1.5 m gives a reduction factor of 380. Thus, after selection, the accidental radioactivity-radioactivity coincidence rate is reduced to 1.1/day.

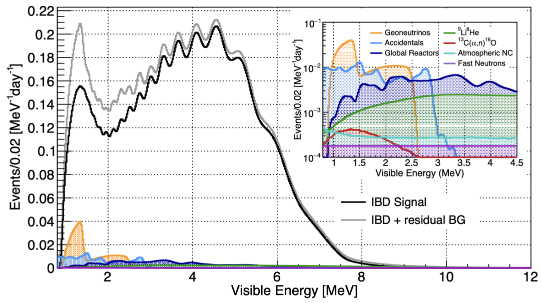

Figure 1: Expected visible energy spectra with (grey) and without (black) background. The inset shows the spectra of the expected backgrounds, mostly located at energy below 4.5 MeV.

Background	Rate (day^{-1})
Geoneutrinos	$1.0 \pm 30\%$
World reactors	$1.0 \pm 2\%$
Accidentals	0.8 ± 1 %
$^{9}Li/^{8}He$	0.8 ± 20 %
Atmospherics	0.16 ± 50 %
Fast neutrons	0.1 ± 100 %
$^{13}C(\alpha, n)^{16}O$	0.05 ± 50 %

Table 1: Source of background and daily rates, the uncertainty on the rate is given as a percentage.

(radioactivity, cosmogenic isotope): The neutron-like singles rate from cosmogenics is estimated to ~340/day. In fine, the rate of accidental coincidence between radioactivity and cosmogenics requiring $\Delta t_{p-d} < 1.0$ ms and a distance between prompt and delayed vertex below 1.5 m is about 0.01/day.

(radioactivity, spallation neutron): The spallation neutron rate of ~1.8 Hz is reduced to about 45/day after the application of the muon veto strategy (described in section 3) and selection cuts. Hence, the residual coincidence rate after muon veto strategy is negligible.

2.2 Fast neutrons background

The cosmic muons that pass through the rock surrounding the WCD and corner clipping muons with short track in water can not be tagged. The fast neutrons produced by those muons can mimic IBD events by producing proton recoils while thermalising and then being captured in the LS. The rate of IBD-like events due to fast neutrons has been estimated to ~0.1/day based on a complete simulation of the detector. The prompt energy spectrum of these events is essentially flat, hence this background has a small impact on JUNO's sensitivity.

2.3 13C induced background

The alpha particles from U and Th decay chains can react with the ^{13}C of the LS. The $^{13}C(\alpha, n)^{16}O$ reaction leads to a correlated background if the neutron is fast enough to produce proton recoils, or, alternatively, if the ^{16}O produces de-excitation gammas. From the estimated concentrations of U and Th, the rate of (α, n) reactions is estimated to 0.05/day.

2.4 Neutrino background (geo, reactors, atmospherics)

Antineutrinos produced in U and Th decay chains from the Earth's mantle and crust constitute the geo-neutrino flux. These neutrinos will also contribute as a background to the reactor antineutrinos. The event rate of geo-neutrinos interacting inside JUNO is estimated to 1.2/day after all selections cuts. The total rate uncertainty is ~30 % with a 18% rate uncertainty for neutrinos emitted in the crust and 100% rate uncertainty for neutrinos emitted in the mantle. JUNO will be able to reduce the current uncertainties on the geo-neutrino rate, to this purpose, local geological studies are ongoing to constrain crustal contribution. In addition to the geo-neutrino flux, the flux of neutrinos emitted in reactors world-wide is estimated to 1.0/day after all selection cuts. Finally, the rate of atmospheric neutrinos has been estimated from simulation within the GENIE framework to 0.16/day.

2.5 Cosmogenic background

Cosmogenic isotopes such as ^{9}Li and ^{8}He are produced by muon showering in the LS. These long-lived isotopes (178 ms and 119 ms respectively) constitute a background because they can undergo a $\beta - n$ decay. Production yields for these isotopes are extrapolated from KamLAND measurement [3]: 150 ^{9}Li/day and 50 ^{8}He/day. Considering the branching ratio to the $\beta - n$ decay: 51% for ^{9}Li and 16% for ^{8}He. The total rate of $\beta - n$ background events is 84/day and reduces to 71/day after selection cuts. In order to further reduce this background, a dedicated muon veto strategy has been designed and will be explained in the next section.

3. Muon veto strategy

To reduce the rate of background events due to cosmogenics, the topological correlation between the muon track and the isotopes position is considered. The detail of the strategy is as follows: For all muons passing through the WCD and or CD a 1 ms veto is applied over the whole FV to suppress spallation neutrons and short-lived isotopes. For well reconstructed single muon tracks in CD: a veto of 600 ms, 400 ms, and 100 ms is applied to events with vertices closer than 1 m, 2 m and 4 m from the track, respectively. For muon bundle tracks (parallel tracks closer than 3 m) constituting 0.6% of the muon events: generally, a single track is reconstructed. The veto is applied around this track with the strategy described above, but the cylinder radius of the vetoed volume is increased according to the separation of the track. For events where no track can be reconstructed, which happens when more than 2 muons pass through the detector at the same time, constituting 2% of the muon events, a 500 ms veto is applied on the FV. Finally, a 1200 ms veto is applied on events reconstructed inside a 3 m radius sphere around a spallation neutron capture. This helps to further reject background events from cosmogenics decay. This veto strategy has an IBD selection efficiency of 91.6% while removing 98.8% of the cosmogenic background, effectively reducing the cosmogenic background rate from 71.0/day to 0.8/day.

4. Conclusion

In this paper, we have assessed the sources of background to the reactor antineutrino signal and their rate after applying the selection cuts (see Table 1) and in particular the muon veto strategy, which has been described in details.

References

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