Snowmass2021 - Letter of Interest

Detecting Antineutrinos from Distant Reactors using Pure Water at SNO+

NF Topical Groups:

☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
☐ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
■ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors

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Collaboration: SNO+

Abstract: SNO+ is a multipurpose neutrino experiment located 2 km underground in a Canadian mine. From September 2017 to July 2019, the SNO+ detector operated as a low-threshold water Cherenkov detector. SNO+ has achieved the highest efficiency to detect neutrons in a pure water Cherenkov neutrino detector, about 50% [1], allowing a search for inverse beta decays (IBDs) from reactor antineutrinos. The nearest nuclear reactor is located 240 km away, and the average distance traveled by reactor antineutrinos that resulted in an IBD at SNO+ was about 600 km. Using about one half-year of livetime, a small number of reactor IBDs is predicted to be distinguished among a few background events. This ongoing analysis can inform non-intrusive detection of nuclear reactor operation, whether using a large liquid scintillator or water Cherenkov detector.

Detecting reactor antineutrinos

Because the number of antineutrinos produced in a nuclear reactor is directly proportional to the thermal power output, detecting whether a nuclear reactor is operational simply requires counting reactor antineutrinos and backgrounds. Reactor antineutrinos are most commonly studied via the IBD reaction: $\overline{\nu}_e$ + p $\rightarrow e^+$ + n. With time-coincident prompt and delayed signals from the positron and the neutron-capture γ, backgrounds generally involve neutrons, but also include accidental coincidences of ambient radioactivity. The neutron-producing backgrounds include (α, n) reactions from radioactive isotopes, atmospheric neutrino interactions, β-n decays from cosmogenically-produced isotopes, cosmogenically-induced spallation neutron interactions, and even geo antineutrino IBDs.

Factors limiting the use of neutron captures in pure water are relatively low detection efficiencies of the 2.2-MeV neutron-capture γ and, in either water or scintillator, difficulties in distinguishing this signal from ambient radioactivity. As a solution, many experiments have used nuclei with relatively large neutron capture cross sections that produce distinctive signals (often higher-energy). The addition of such isotopes requires funds and effort, which, on top of basic concerns associated with the safety and stability of deploying liquid scintillator, indicate the potential value in maximizing the efficiency to identify neutrons in a pure water Cherenkov detector. SNO+ achieved an approximately 50% efficiency to detect the 2.2-MeV γ without dedicated effort, and found that this could be improved upon with changes to the readout electronics [1]. Assuming that data acquisition rates are not a limitation, a straightforward approach to increasing the detection efficiency (lowering the detector energy threshold) is to increase light collection by using more PMTs or using PMTs with higher quantum efficiencies. When data rates are a concern, special triggering schemes can temporarily lower the detector threshold, as implemented by the Super-K collaboration [2].

Reactor antineutrinos in SNO+ water

In addition to the thermal power output by the reactor, the number of detected antineutrinos depends on the distance to the reactor and the size of the detector, as well as the detection efficiency. For SNO+, the volume of water within a spherical acrylic vessel was 905 tonnes. The nearest reactor complex to SNO+ is Bruce, which is 240 km distant and comprises the most powerful set of reactors currently active. Along with the Pickering and Darlington complexes, which are 340 km and 350 km distant, these three Canadian complexes account for a little less than 60% of IBDs in the SNO+ detector. With nearly 100 reactors across the USA, the average baseline of SNO+ is around 600 km. In contrast, the KamLAND collaboration has studied antineutrinos from reactors using 1000 tonnes of liquid scintillator at an average baseline of 180 km [4].

Regardless of whether SNO+ makes a first identification of reactor antineutrinos in pure water, it will set a precedent for such analyses and will produce the lowest energy analysis from a large Cherenkov neutrino detector. In particular, it includes informative analyses of (α, n) and atmospheric neutrino backgrounds in water. The ongoing analysis is briefly described in the next section.

Analysis

Two techniques are used in a blinded search for reactor antineutrinos: likelihood and boosted decision tree (BDT). First, a set of basic cuts is applied to remove instrumental effects, select a fiducial volume, and ensure the quality of event reconstruction. This includes a cut on prompt event energy at 2.5 MeV to avoid overwhelming radioactivity. Distributions of other quantities, such as reconstructed energy and distance between events, are used in the likelihood or BDT to derive a single multivariate parameter to cut.

The predicted rate of IBD reactions is about 110 per year within the water-filled acrylic vessel. Applying the basic cuts, which include the efficiency of the detector trigger, reduces this to about 11 IBDs per year. With a livetime of 190 days, about 6 IBDs are expected after the basic cuts.

The accidental background is predicted directly using data. Atmospheric neutrinos are measured in energy and neutron multiplicity sidebands, and predicted with GENIE and extrapolated from Super-K measurements. (α, n) backgrounds are measured in a fiducial volume sideband around the acrylic vessel and predicted from nuclear databases, assays of the acrylic vessel, and a water/acrylic leaching model. Cosmogenic backgrounds are negligible due to the low muon flux, which allows a long (20-second) veto window. And the 2.5-MeV energy cut for prompt events reduces geo antineutrino efficiency to a negligible level.

Optimized cuts on the likelihood and BDT reduce the number of accidentals by a factor of $\sim 10^4$ at the cost of about half of the remaining signal (see Fig. 1), leaving ~ 3 expected signals in 190 days of livetime. Using the water external to the acrylic vessel may enable the fiducial volume to be approximately doubled. Though the rate of radioactivity is higher there, it is primarily inward-pointing, which can be discriminated against. Also, data from an earlier 148 days of livetime have been processed, but they have much higher levels of radon as they were acquired before the installation of the cover gas system.

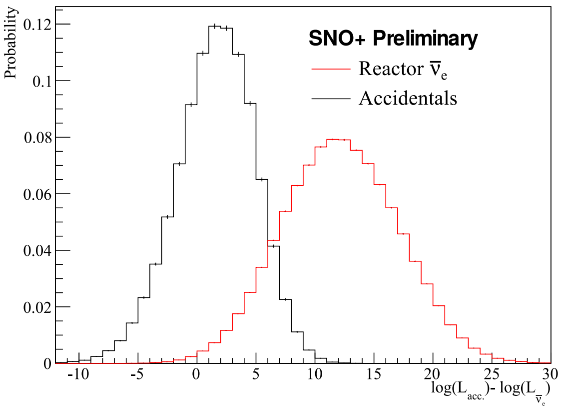

Figure 1: Log likelihood difference distribution of the predicted reactor antineutrino IBDs (red) and accidental background (black) in the SNO+ detector filled with 905 tonnes of water.

Implications

During its water phase, SNO+ acquired data with 905 tonnes of water and a 50% efficiency to detect neutrons across most of the volume. It is expected to identify roughly three reactor antineutrino IBDs among a few background events within 190 live days of data. The nearest nuclear reactor complex is 240 km away and contributes roughly 40% of the total incident flux. Extrapolating the expectations discussed above for a similarly-sized detector placed 15 km from a single reactor core of about 1.0 $\mathrm{GW}_{\mathrm{th}}$, a highly confident determination of reactor operation could be determined in less than three months.

This extrapolation assumes similar backgrounds as the SNO+ analysis, which certainly depends on ambient radioactivity and the ability to suppress cosmogenic backgrounds. However, with a livetime that is shorter by more than a factor of two, the number of background events would reduce by the same factor. And though scintillator detectors do have detection efficiencies greater than those of Cherenkov detectors, this is not a fundamental limitation of the latter. If needed, the efficiency of pure water Cherenkov detectors like SNO+ could be raised by increasing the coverage of PMTs or the PMT quantum efficiency.

References

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