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Reactor monitoring with direction-sensitive detectors

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Abstract.
Nuclear power reactors account for a small fraction of the Earth's total antineutrino ($\overline{\nu}$) luminosity. Past experiments, with baselines between ~10 m and ~1000 km, have successfully measured the rate and spectrum of reactor-born $\overline{\nu}_e$s. Additionally detecting the incident direction of reactor $\overline{\nu}_e$s would constitute an important milestone in the development of reactor monitoring for nuclear non-proliferation since this information could aid in identifying undeclared nuclear reactors. Here we examine the prospects of using low-background, direction-sensitive tracking detectors to remotely monitor nuclear reactors. For an experiment sited at SNOLab, we calculate that an exposure of 56–78 (31–46) tonne-months is needed to detect the flux of $\overline{\nu}_e$s produced by a 3758-MW reactor at a distance of 13 km at 95% (90%) confidence level.

1. Introduction

Antineutrino detection methods can serve as a practical, non-intrusive tool for remotely monitoring the activity of nuclear reactors, as well as a potential safeguard for preventing nuclear proliferation. A strategic goal of reactor monitoring is to remotely detect a change in the operational status of a reactor, since harvesting of weapons-grade nuclear material (^{239}Pu) typically requires periodic shutdowns to remove it from the reactor before it degrades. The proposed WATCHMAN experiment [1] aims to detect the on/off state of a civil reactor via the detection of inverse beta decay on free protons, $\overline{\nu}_e p \to e^+ n$, using a ~1-ktonne Gd-doped water Cherenkov detector. In one of two possible scenarios, the experiment will be located 13 km away from a 3758-MW light water reactor, giving it the opportunity to measure reactor characteristics such as operational status, relative power output and evolution of the isotopic fuel composition (burnup). Additionally measuring the direction of incident antineutrinos would constitute an important milestone for reactor monitoring since it could aid in identifying undeclared reactors.[1]

We discuss a method for measuring the rate, energy and direction of incident neutrinos using neutrino-electron (ν_e-e^-) elastic scattering in low-background, direction-sensitive tracking detectors. Unlike the inverse beta decay reaction above, elastic scattering preserves event-by-event directional information, since the direction of the outgoing electron is correlated with the direction of the incoming neutrino. This directional information can be exploited in order to select signal events, reject backgrounds and locate undeclared reactors. For an experiment sited at SNOLab, Canada, we calculate the exposure needed to detect the flux of reactor-$\overline{\nu}_e$s from a 3758-MW reactor positioned 13 km away at 95% (90%) confidence level, treating all other neutrino sources as background.

[1] Directional reconstruction capability of the proposed WATCHMAN experiment has been studied in [2].

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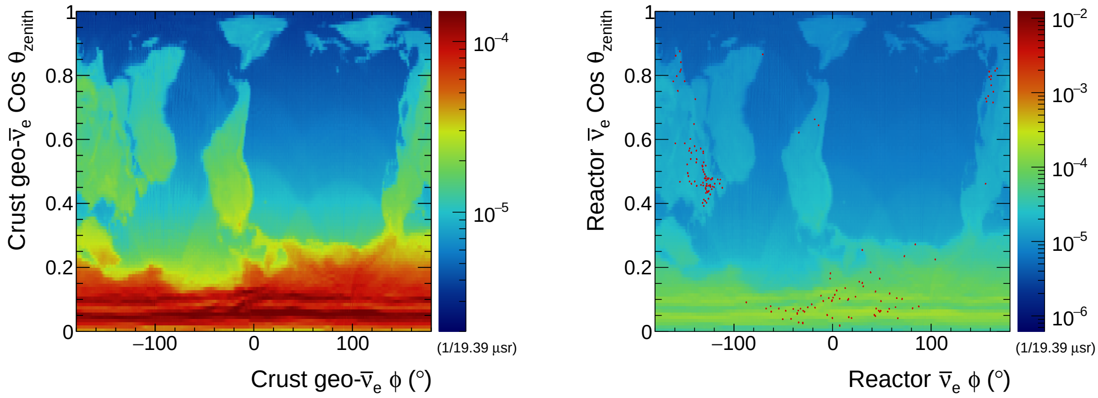
2. Neutrino backgrounds

The dominant source of irreducible background to ν_e-e^- elastic scattering comes from elastic scattering of other neutrinos, primarily solar ν_es. Here we consider the following neutrino fluxes: solar ν_es from the Sun; geo-$\overline{\nu}_e$s from the Earth's crust and mantle; and reactor $\overline{\nu}_e$s from worldwide nuclear power reactors. Interaction rates for atmospheric and relic supernova neutrinos are estimated to be negligible.

Solar-ν_e flux predictions are taken from a recent global analysis [3] of solar and terrestrial neutrino data in the framework of three-neutrino mixing. While solar ν_es are the dominant neutrino background for this analysis, a detector with the ability to measure the direction of incident neutrinos has additional rejection power against such events since the solar-ν_e background points back to the Sun. Using the electron angle, energy and the position of the Sun at the time of interaction, we show that a direction-sensitive detector can, in principle, reject most of the solar-ν_e background.

Geo-neutrinos, produced by the β^- decays of radiogenic isotopes in the Earth's crust and mantle, account for 96–99% of the Earth's $\overline{\nu}_e$ luminosity. We use previous measurements [4–9] of geo-$\overline{\nu}_e$s to constrain our model prediction and estimate the background due to geo-$\overline{\nu}_e$s at SNOLab [10]. Directions to geophysical structures are mapped using CRUST 1.0 [11] and the Preliminary Reference Earth Model [12]. Details of the calculation, including the predicted geo-$\overline{\nu}_e$ fluxes, are given in [10]. The predicted incident angular distribution of geo-$\overline{\nu}_e$s from the Earth's crust at SNOLab is shown in Fig. 1a.

The intensity of $\overline{\nu}_e$s produced and emitted by worldwide nuclear power reactors is calculated at SNOLab using positions and maximum powers of currently operating cores [13, 14] and assuming a spherical Earth. We use fission fractions from [13] to calculate the $\overline{\nu}_e$ spectra for each reactor type, to be published at a later date. Figure 1b shows the predicted incident angular distribution of $\overline{\nu}_e$s from worldwide nuclear power reactors at SNOLab.



(a) (b)

Figure 1. Angular distribution of incident antineutrinos, calculated at SNOLab (Canada), from: **(a)** the Earth's crust; and **(b)** worldwide nuclear power reactors. The azimuthal angle ϕ is measured clockwise from due North, while the zenith angle θ_{zenith} is measured with respect to the vertical axis, defined opposite the direction pointing to the center of the Earth. **(a)** Crust geo-$\overline{\nu}_e$ distributions are derived using CRUST 1.0 [11] and PREM [12], supplemented with detailed topological information for $\cos\theta_{\text{zenith}} < 0$. **(b)** The directions to nuclear power reactors [13] are shown here in red, superimposed on the crust geo-$\overline{\nu}_e$ map for visualization. All plots are normalized to unit volume.

3. Direction-sensitive detectors

We simulate a gas-filled time projection chamber (TPC), based on the performance of past detectors [15–17] that have successfully reconstructed the direction of low-energy recoils in low-background environments. In a search for anomalous neutrino magnetic moment using $\overline{\nu}_e$-e^- elastic scattering, the MUNU collaboration [16] demonstrated electron energy and direction reconstruction performance in a 1 m^3 TPC, filled with CF_4 gas at 1 bar and instrumented with wire and strip readout at a pitch of 4.95 mm. The electron energy (T) resolution [16] was determined to be 10% at 200 keV and 6.8% at 478 keV, scaling as $T^{0.57}$. The measured electron angular resolution [15, 16] varied from 15° at 200 keV, to 12° at 400 keV, to 10° at 600 keV. A best fit to these data points yields an energy dependence, σ_θ [°] $= 102\,T^{-0.361}$, with T in keV. The impact of assuming this angular resolution parameterization on the calculated exposures is discussed in Section 6.

4. Event rates

Event rates per tonne-month exposure are calculated as a function of recoil electron kinetic energy, assuming a CF_4 target, using the ν_ℓ-e^- differential elastic scattering cross section (for both ν_ℓ and $\overline{\nu}_\ell$) from [18, 19]. Our calculation includes the effect of oscillation, $\nu_e \to \nu_\mu, \nu_\tau$ and subsequent ν_μ-e^- or ν_τ-e^- elastic scattering. The predicted event rates, including the effect of oscillation, are shown in Fig. 2. An energy threshold of 700 keV is chosen in the following section in order to optimize the calculated sensitivity and ensure that the direction of the electron recoil, despite scattering and smearing, is well correlated with the direction of the incident neutrino.

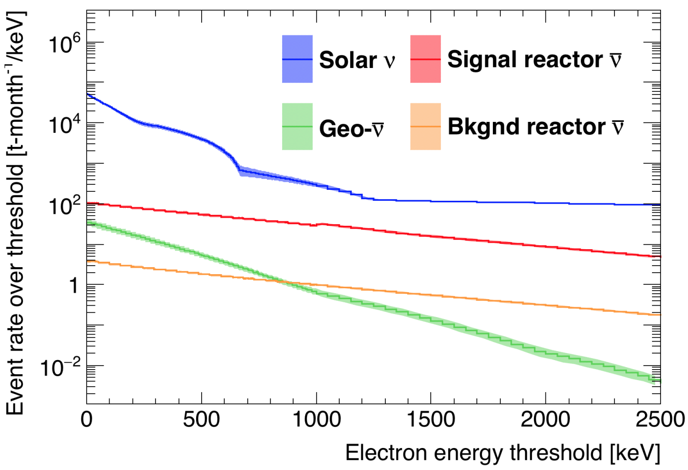


Figure 2. Predicted event rates over threshold per tonne-month exposure versus electron energy threhsold (keV) for solar-ν_ℓ (blue), geo-$\overline{\nu}_\ell$ (green), background reactor-$\overline{\nu}_\ell$ (orange) and signal reactor-$\overline{\nu}_\ell$ events (red), assuming a CF_4 target and 45% probability of oscillation into ν_μ or ν_τ. Error bands shown here correspond to uncertainties given in Section 5. Event rates are approximately 0.4% higher for a SF_6 target or 13.8% lower for a Xe target.

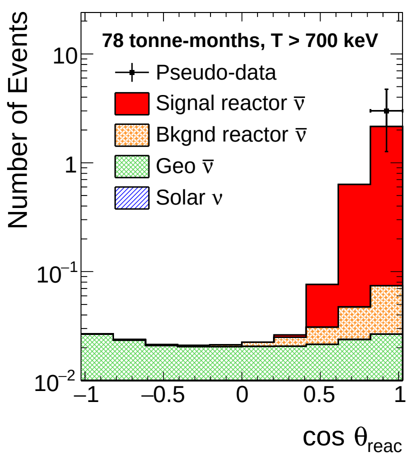
5. Sensitivity analysis

Using the methodology developed in [10], we calculate the exposure needed to detect the flux of reactor $\overline{\nu}_e$s emitted by a hypothetical 3758-MW reactor positioned 13 km away from SNOLab at 95% (90%) confidence level (CL), treating all other neutrino sources as background. Briefly, we simulate many pseudo-experiments and use a profile likelihood statistic to assess the exposure required to either set an upper limit for background-only (reactor-off) pseudo-experiments, or exclude the null hypothesis for signal + background (reactor-on) pseudo-experiments at 95%, or 90%, CL.

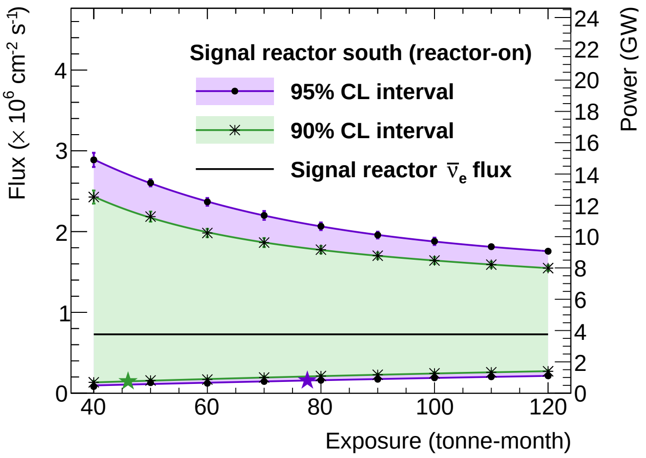
Reconstructed angles and electron energies are smeared with Gaussian distributions according to the resolutions given in Section 3. An energy threshold of 700 keV is applied. Solar-ν_ℓ events are rejected by cutting on the angular separation from the Sun at the time of interaction, θ_{sun}.

The measured spectrum of all recoil electrons with energy $T > 700\,\text{keV}$, following scattering and angular smearing, is fit with a von-Mises distribution summed with a flat pedestal [10]. The results of the fit are used to remove events that lie outside of the range $\mu \pm 3.5\sigma$, or $\cos\theta_{\text{sun}} < 0.59$. This cut accepts, on average, 77% of crust geo-$\overline{\nu}_\ell$ events, 80% of mantle geo-$\overline{\nu}_\ell$ and background reactor-$\overline{\nu}_\ell$ events, 0.16% of solar-ν_ℓ events, and 80–82% of signal reactor-$\overline{\nu}_\ell$ events.

To understand the dependence of the calculated sensitivity on the position of the signal reactor relative to nearby background reactors, we study two scenarios: one in which the signal reactor is positioned due south of SNOLab (total overlap with background reactors in the United States) and another in which the signal reactor is due north of SNOLab (little to no overlap with background reactors). We define θ_{reac} as the angular separation between the electron recoil direction and the vector pointing from the signal reactor to the detector. The θ_{reac} distribution for a signal + background reactor-south pseudo-experiment at SNOLab is shown in Figure 3a. Background solar-ν_ℓ and geo-$\overline{\nu}_\ell$ events are distributed isotropically from $-1 \leq \cos\theta_{\text{reac}} \leq 1$, while signal and background reactor-$\overline{\nu}_\ell$ events mostly point parallel to the reactor-detector direction ($\cos\theta_{\text{reac}} \approx 1$), making background discrimination difficult and adversely affecting the sensitivity. The results of the sensitivity analysis for the signal + background reactor-south scenario are shown in Fig. 3b.



(a)



(b)

Figure 3. Sensitivity of a direction-sensitive detector to a 3758-MW reactor located 13 km south of SNOLab (Canada). **(a)** Angular distribution of electron recoils induced by signal reactor $\overline{\nu}_e$s (red solid), background reactor $\overline{\nu}_e$s (orange weave), geo-$\overline{\nu}_e$s (green hatched) and solar ν_es (blue striped), relative to the direction from the signal reactor, normalized to an exposure of 78 tonne-months and including the effect of neutrino oscillation. Pseudo-experimental data (black squares) are also shown, with their statistical errors. A cut requiring a minimum angular separation from the Sun (θ_{sun}) has been applied. **(b)** Mean 95% (90%) confidence interval for signal + background (reactor-on) pseudo-experiments versus exposure. The star-shaped markers represent the exposures at which 95% (90%) of pseudo-experiments have a non-zero lower limit.

When calculating the profile likelihood statistic, we apply a flat ±7% systematic uncertainty on the pseudo-data, intended to cover measurement uncertainties on the global acceptance, track reconstruction efficiency, cross section, number of targets in the fiducial volume, energy resolution and angular resolution, in addition to uncertainties on oscillation parameters. This value is consistent with the systematic uncertainty reported by the MUNU collaboration [15]. Uncertainties on the solar-ν_e fluxes are taken from [3] and propagated to the solar-ν_ℓ event rate, resulting in a +26.1% and −13.4% change in the predicted event rate for an energy threshold of 700 keV. A ±6% uncertainty on the reactor-$\overline{\nu}_e$ flux and corresponding event rate is also applied to cover uncertainties on the energy spectrum, reactor powers and oscillation parameters [10]. A ±18% systematic uncertainty is applied on the geo-$\overline{\nu}_\ell$ background at SNOLab [10], calculated from uncertainties on geophysical and geochemical modeling and using constraints from existing measurements of geo-$\overline{\nu}_e$s [4–9].

6. Discussion

We find that direction-sensitive detectors at the multi-tonne-scale are sensitive to the flux of $\overline{\nu}_e$s emitted by a 3758-MW nuclear reactor at a distance of 13 km. The dependence of the required exposure on the angular separation between signal reactor and background reactors was studied. For a detector sited at SNOLab and a signal reactor due north of the experimental site, we estimate that an exposure of 56 (31) tonne-months is needed to exclude the null hypothesis and set a non-zero 95% (90%) CL lower limit for 95% (90%) of signal + background (reactor-on) pseudo-experiments. An exposure of 61 (43) tonne-months is needed to set a 95% (90%) CL upper limit equal to the predicted flux from the signal reactor for background-only (reactor-off) pseudo-experiments. For a signal reactor due south of SNOLab, we calculate that an exposure of 78 (46) tonne-months is needed to exclude the null hypothesis at 95% (90%) CL, while an exposure of 64 (45) tonne-months is needed to set a 95% (90%) CL upper limit equal to the predicted flux.

The exposures quoted here assume a CF_4 target and direction reconstruction performance previously demonstrated by the MUNU experiment. Enhancing the detector angular resolution by a factor of 2 reduces the required exposures by 12% (7%) for reactor-on pseudo-experiments or by 7% (7%) for reactor-off pseudo-experiments. The exposures above also assume perfect rejection of non-neutrino backgrounds, namely those due to radioactive contamination of the detector or shield materials, intrinsic radioactivity or cosmogenic activation of the gas target, or other backgrounds coming from the cavern walls. The impact of these non-neutrino backgrounds on the calculated exposures is discussed in [10].

Acknowledgments

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