Sensitivity of Neutrino Detectors to Reactor Burnup: IBD and CEνNS Comparison

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Introduction

Resolving changes in the ^{239}Pu fission fraction during a reactor fuel cycle is central to monitoring applications. Neutrino-based approaches provide a non-intrusive probe, with sensitivity determined by both detector response and interaction channel. Traditional monitoring relies on inverse beta decay (IBD), which yields well-defined energy spectra but requires ton-scale detectors. An alternative is coherent elastic neutrino–nucleus scattering (CEνNS), whose enhanced cross section enables compact detectors with sub-keV thresholds. Despite challenges such as low recoil energies and strict background requirements, CEνNS remains a promising avenue. In this work, we compare the sensitivity of an optimistic CEνNS configuration with that of a conventional IBD detector to variations in the ^{239}Pu fission fraction over a typical light water reactor fuel cycle.

Methodology

The IBD detector considered is a 1 ton liquid scintillator located 30 m from a 3 GW$_{\mathrm{th}}$ reactor, with a background rate of 0.1 events/MeV/ton/day, a systematic uncertainty of 3%, an overall detection efficiency of 40%, and a live time of 80%[1]. The detector response is modeled with a resolution function $\sigma(E) = \sqrt{aE + bE^2}$ with parameters $a = 0.02$ MeV, $b = 0.0025$, applied to fold the prompt spectrum in 100 keV bins.

Figure 1 shows the change in the prompt event rate across the IBD energy range between two points in the reactor burnup cycle with a ^{239}Pu fission fraction difference of 0.04 and a 30-day exposure.

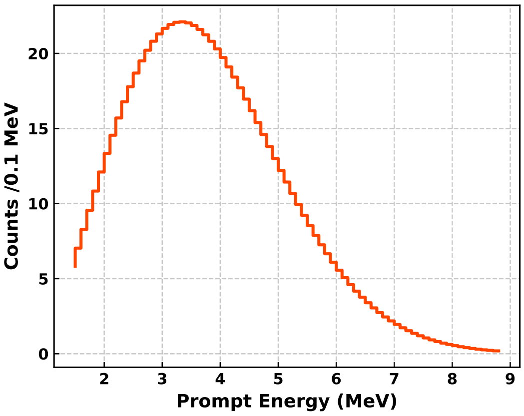

FIG. 1: Difference in prompt event rates for a 1 ton liquid scintillator IBD detector between two burnup points with $\Delta f_{239} = 0.04$, assuming 30 days of exposure. The spectrum is folded with the detector response function and binned in 100 keV intervals.

The CEνNS detector is an array of cryogenic germanium detectors with phonon sensors, a fiducial mass of 100 kg, a background rate of 10 events/keV/kg/day[3], a systematic uncertainty of 0.1%, a 50 eV energy threshold, 80% phonon conversion , and an overall detection efficiency of 80% with 80% live time. Its response is modeled by $\sigma_{ee}(E) = \sqrt{\sigma_0 + (aE_{ee})^2 + bE_{ee}}$ [2] with $\sigma_0 = 9.8\ eV_{ee}$, $a = 0.005$, $b = 0.8\ eV_{ee}$, applied to fold the recoil spectrum in 50 eV bins.

Figure 2 displays the corresponding difference in nuclear recoil rates across the phonon energy range for the same change in ^{239}Pu fission fraction and exposure. The differences are concentrated at the lowest energies,

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*Electronic address: `sahur@barc.gov.in` reflecting the coherent nature of neutrino-nucleus scattering and the sub-keV sensitivity of phonon-based detectors. This highlights the complementary ability of CEνNS to probe subtle isotopic changes that are inaccessible to IBD measurements.

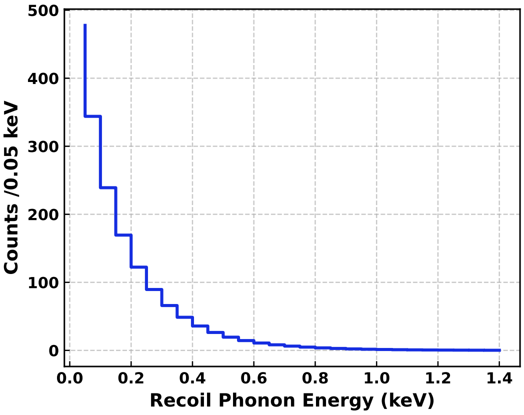

FIG. 2: Difference in nuclear recoil rates for a 100 kg cryogenic germanium CEνNS detector between two burnup points with $\Delta f_{239} = 0.04$, assuming 30 days of exposure. The spectrum is folded with the detector response and binned in 50 eV intervals.

Results & Discussion

To quantify the sensitivity of the detectors to changes in reactor fuel composition, we compute the χ^2 difference between spectra at different ^{239}Pu fission fractions for varying exposure times, using

$$\chi^2 = \frac{a^2}{\sigma_a^2} + \frac{\Big((1+a)N_i(f_{239}) - N_i(f_{239}^{ref})\Big)^2}{\sigma_{stat}^2 + \sigma_{sys}^2} \tag{1}$$

Figure 3 summarizes the resulting detector sensitivity: it shows the minimum resolvable difference in ^{239}Pu fission fraction at 90% and 99.7% confidence levels as a function of exposure for the IBD and CEνNS configurations. For a typical light water reactor, the ^{239}Pu fission fraction changes by ~ 0.28 over the course of a year. With exposures of a few tens of days, both detectors can resolve differences of about 0.05, while CEνNS offers improved sensitivity of ~ 0.01 at 99.7% C.L. and ~ 0.005 at 90% C.L. This demonstrates the potential of CEνNS to probe subtle isotopic changes in reactor cores on shorter timescales compared to IBD detectors.

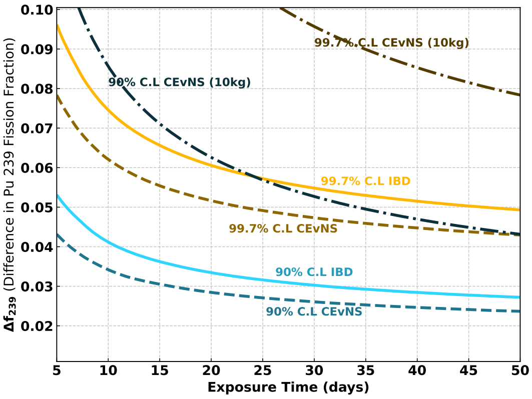

FIG. 3: Minimum resolvable change in ^{239}Pu fission fraction for the IBD and CEνNS detectors as a function of exposure time, shown at 90% and 99.7% confidence levels.

The contours show that a 100 kg CEνNS detector resolves changes in the ^{239}Pu fission fraction at about half the exposure required by IBD. The sensitivity performance of a realistic 10kg reference configuration is also presented for comparison. The CEνNS parameters considered are optimistic, and the results serve only to evaluate sensitivity and feasibility rather than propose an immediate alternative to IBD. Practical issues such as scalability, background suppression, and long-term stability remain significant challenges.

References

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[3] N. Ackermann et al., Eur. Phys. J. C **84**, 1265 (2024)