Study of reactor antineutrino flux evolution using coherent elastic neutrino nucleus scattering

Rashmi Ranjan Sahu[1], Kirtikesh Kumar[1], S.P. Behera[1,2], R. Sehgal[1], D.K. Mishra[1,2], and V. Jha[1,2*]
[1] *Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA and*
[2] *Homi Bhabha National Institute, Anushaktinagar, Mumbai - 400094, INDIA*

Introduction

Coherent elastic neutrino nucleus scattering (CEνNS) is a Standard Model interaction where neutrinos scatter off all nucleons in a nucleus, greatly increasing the scattering cross-section. This allows for the use of compact detectors of kilogram size, but the low energy of nuclear recoils requires sensitive, low-threshold detectors. The anti-neutrino flux from a reactor is produced by the beta decay of fission products, which depends on the reactor's fuel composition. As Pu-239 is bred during the fuel cycle, the anti-neutrino spectrum and nuclear recoil spectrum change over time, with increasing contributions from Pu-239 decay.

The main fission isotopes contributing antineutrino flux in a reactor are ^{235}U,^{239}Pu, ^{238}U and ^{241}Pu. The presence of plutonium is due to breeding reactions, which occur in all reactors that use natural or low-enriched uranium. These reactions proceed through neutron captures and beta decays. Each of these isotopes has distinct and well-defined neutrino emissions, with differing energy spectra and neutrino counts. By observing the number and spectra of neutrinos emitted by reactors, one can determine the composition of the reactor fuel.

Calculations

The differential cross-section of CEνNS is predicted within the Standard Model by the formula

$$\frac{d\sigma}{dE_{\rm rec}} = \frac{G_F^2 m_A}{4\pi}\left(1 - \frac{m_A E_{\rm rec}}{2E_\nu^2}\right) Q_W^2 \quad (1)$$

$$Q_W = Z(1 - 4\sin^2\theta_W) - N$$

where Q_W denotes a weak charge, G_F is the Fermi coupling constant, m_A is the nuclear mass of the target, $E_{\rm rec}$ is the nuclear recoil energy, and E_ν is the neutrino energy, $Z(N)$ is the atomic number (neutron number) of the nuclei and θ_W is the Weinberg or weak mixing angle. The differential rate combines the neutrino flux and the differential cross-section to yield

$$\frac{dR}{dE_{\rm rec}} = n_t \int_{E_{\rm thr}}^{\infty} dE_\nu \Phi(E_\nu) \frac{d\sigma}{dE_{\rm rec}}(E_\nu) \quad (2)$$

where n_t is the number of target nuclei and $E_{\rm thr} = \sqrt{E_{\rm rec} m_A/2}$ represents the threshold neutrino energy. The anti-neutrino flux at the detector $\Phi(E_\nu)$ is a sum of contributions due to different isotopes and the typical fission fractions in a LWR are 57.7% of ^{235}U, 29.6% of ^{239}Pu, 7.2% of ^{238}U and 5.5% of ^{241}Pu[1].

Results & Discussion

The nuclear recoil spectrum is obtained using the parametrized anti-neutrino spectrum[2] of each fissile isotope assuming the total flux to be due to that particular isotope only and is shown in Figure 1. The differences in counts between ^{235}U, and ^{239}Pu is the fundamental motivation for the feasibility of measurement of ^{239}Pu content in the reactor. As the fuel cycle continues, the total CEνNS yield decreases due to increasing contribution from ^{239}Pu which has lower anti-neutrino flux[3]. This is shown in Figure 2

*Electronic address: `vjha@barc.gov.in`

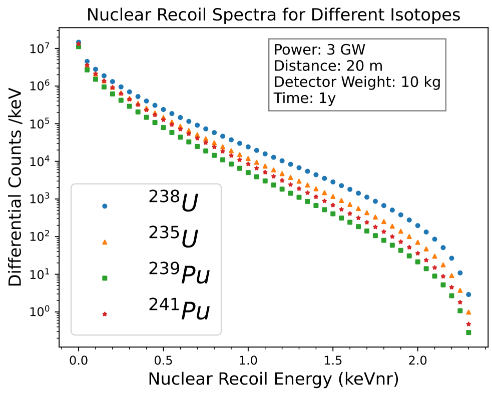

FIG. 1: The nuclear recoil spectrum assuming the entire anti-neutrino flux to be due to a single fissile isotope.

for a typical LWR with initial fission fraction as specified in earlier section for a thermal power of 3 GW at a 10kg HPGe detector assuming a threshold of 0.5 keVnr, placed 20m from the reactor core, where the average reduction in counts was calculated to be ~ 70 over a measurement cycle of 60 days for a change in fission fraction of $\delta F_{239} = +0.03$. The detection threshold is critical because

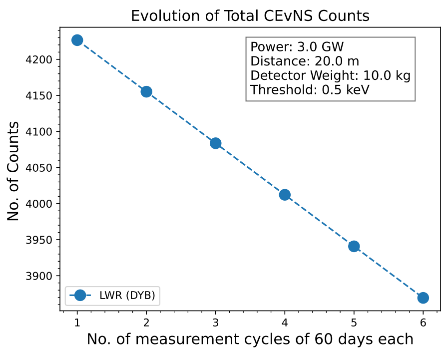

FIG. 2: The evolution of CEνNS yield over a fuel cycle for a typical LWR.

the CEνNS cross-section is highly sensitive to the energy of the nuclear recoil, meaning even a slight increase in the threshold can drastically reduce the detectable events.

The evolution of the fuel composition also results in a change in shape of the nuclear recoil spectrum that is represented by the different rate of change in CEνNS counts with time for different nuclear recoil energy bins as shown in Figure 3. This indicates that the fractional decrease in yield is not uniform over the entire range of E_{rec} but varies significantly.

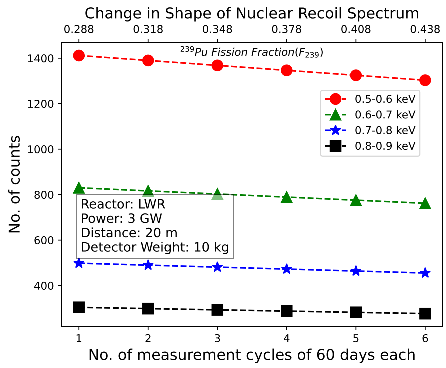

FIG. 3: The different rates of change in CEνNS yield with time for different nuclear recoil energy bins.

Conclusion

These results illustrate the potential applications of CEνNS in determining the breeding of ^{239}Pu over a fuel cycle in a non intrusive way using compact low threshold germanium detector. Due to the low number of observable events over the detection threshold, background suppression is crucial and imposes stringent shielding requirements. The measurement of change in shape of the recoil spectrum however necessitates an even lower threshold to resolve the detectable signal over the background due the smaller size of recoil energy bins.

References

[1] P. Huber, Nucl. Phys. B **908**, 268-278 (2016)

[2] P. Huber, Phys. Rev. C **84**, 024617 (2011).

[3] F. An et al. (DAYA-BAY Collaboration), Phys.Rev.Lett. **108**, 171803 (2012), 1203.1669.