Simulation and conceptual design of a detector for sterile neutrino search and remote reactor monitoring

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Introduction

The calculation of measured/expected ratio of antineutrinos coming from reactors at detector distances <100 m, shows a value less than unity at a C.L of 98.2%. This has been termed the *Reactor Antineutrino Anomaly* [1]. The reactor antineutrino anomaly cannot be understood within the usual 3 neutrino framework. It is well explained if a fourth flavor known as the sterile neutrino mixes with the $\bar{\nu}_e$ with $\Delta m^2 \sim 1$ eV^2 leading to a deficit in the measured number of $\bar{\nu}_e$ at these distances. Fig. 1 depicts a first order calculation of the variation of ratio (R) of the survival probability of the reactor antineutrino with oscillation to the survival probability without oscillation, with distance. For this purpose, neutrinos generated using Monte Carlo technique anywhere within a cylinder of dimension typical to the core of the DHRUVA reactor at BARC, and traveling to a detector of 1 m^2 front face area, were used.

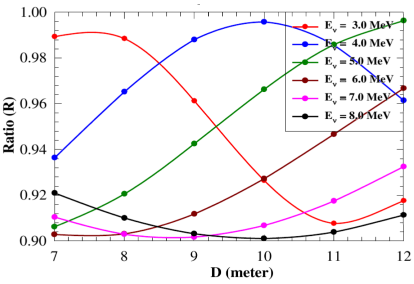

FIG. 1: Ratio of survival probability as a function of distance for different neutrino energies ($\sin^2 2\theta = 0.1$ and $\Delta m^2 = 1$ eV^2).

Simulation & detection principle

The detector, modeled using the simulation toolkit GEANT4 [2], is as follows. It consists of 100 scintillator bars, each having a dimension of 100 cm × 10 cm × 10 cm arranged to form a cube of 1 m^3. Each bar is wrapped with a 25 μm mylar foil coated with Gadolinium paint ($\sim$ 4 mg/cm^2). The scintillator ($C_{10}H_{11}$) material with a density of 1.032 g/cm^3 will act as the target as well as the detector. Antineutrinos from the reactor interact with protons in the scintillator, via the Inverse Beta Decay (IBD) process

$$\bar{\nu}_e + p \rightarrow n + e^+. \qquad (1)$$

The positron which carries almost all of the energy brought in by the antineutrino rapidly loses its energy in the scintillator and gets annihilated producing two gamma rays. The energy loss of the positron constitutes the 'prompt' signal along with the Compton scattered annihilation gamma rays adding an additional energy 1.02 MeV (maximum). Hence,

$$E_{\text{signal}} = E_{\bar{\nu}_e} - 1.8 \text{ MeV} + 2m_e c^2 \qquad (2)$$

On the other hand, the neutron which carries an energy ~10 keV gets thermalised in the scintillator and eventually gets captured in 'Gd' producing a cascade of gamma rays with total energy adding up to ~8 MeV. The energy deposited by these gamma rays in the scintillator provides a 'delayed' signal. The correlation between the prompt and the delayed signal uniquely identifies the IBD event. Fig. 2 shows the capture time distribution in the above mentioned geometry obtained using GEANT4. The QGSP-BIC-HP physics package is chosen for modeling the thermalization and capture of the neutrons. For neutron energies below 20 MeV, the high-precision

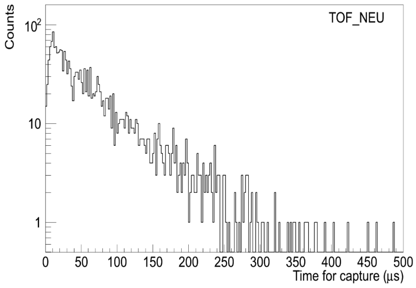

FIG. 2: Capture time distribution of the neutrons produced in the IBD process modeled in GEANT4.

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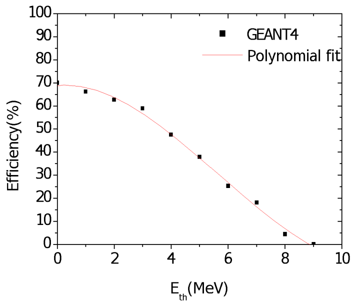

FIG. 3: Efficiency of the detector as a function of $E_{\rm th}$, the energy threshold on the 'delayed' signal.

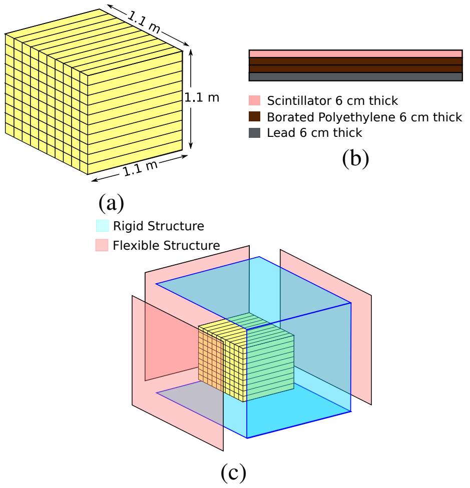

FIG. 4: (a) Scintillator Matrix. (c) The layers of the shield. (b) Scintillator Matrix with the shielding.

package uses the ENDF/B-VII data library [3]. Fig. 3 shows the simulated efficiency of the detector as a function of the energy deposited by the 8 MeV gamma cascade in the the volume.

Conceptual design

The detector will have a scintillator matrix (SM), in which each scintillator will be coupled to two photomultipliers at either ends. A dimension of 110 cm × 11 cm × 11 cm for each scintillator is under consideration so that photomultiplier of 3″ ⊘ will be compatible with scintillator cross section of 11 cm × 11 cm. There will be 100 scintillators and 200 PMTs. These scintillators will be stacked in a way so that the complete detector size would be a cube of dimension 110 cm × 110 cm × 110 cm. Simulations will be performed for this dimension and then optimized. The scintillators will be wrapped by aluminized Mylar with 'Gd' painted on the non reflective side. The thickness of the coat will be 12.5 μm having a density of 4.9 mg/cm^2, which are commercially available. The PMTs will be directly coupled to the scintillator without light guides. The scintillator matrix (SM) is shown in Fig. 4(a). From the SM, moving outwards, on all the six sides, there would be 6 cm of Pb (for gamma shielding), followed by two layers each of 6 cm of borated polyethylene (for neutron shielding) and lastly a layer of 6 cm thick scintillator to veto cosmic muons, as shown in Fig. 4(b). Since the detector will be placed at a very short distance (10 m) from the reactor, it should be hermetically shielded from background radiations, as shown in Fig. 4(c). The blue and pink colors show the rigid and flexible structures respectively. The gross weight of the detector without supporting structures will be ~22 t. It is proposed to be placed in the DHRUVA reactor hall, at BARC.

Reactor Monitoring

Antineutrinos emitted by the fission products provide real time information of the fission process occurring in the reactor core. During a reactor cycle (PWR), ^{235}U is burned while ^{239}Pu is produced. The number of antineutrinos emitted per fission of 'Pu' is less than that of 'U', a reactor running at constant power ($P_{\rm th}$) will have a neutrino emission rate (N_ν) decreasing over the time for a given cycle.

$$N_\nu = g(1 + k(t))P_{\rm th} \tag{3}$$

where g is a constant and $k(t)$ is the fuel composition (burnup) which evolves with time [4, 5]. This can be used to monitor reactors remotely. Assuming a detection efficiency of 50% and thermal power of 50 MW for the DHRUVA reactor, one can expect around 200 antineutrino events/day at a distance of 10 m.

References

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