Simulation of detector response for antineutrino induced events with a proto-type plastic detector array

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Introduction

The phenomena of neutrino oscillation have been established by several experiments using neutrinos from different sources. The present challenges in the neutrino-physics are to find out the maximality of mixing angle, mass hierarchy of neutrinos, absolute mass of neutrinos and the existence of sterile neutrino etc. Apart from these fascinating physics aspects, the measurement of the antineutrino spectrum from the reactor has found applications in monitoring of the power history and fissile inventory of a nuclear reactor [1]. In a nuclear reactor, antineutrino emission takes place from the beta decay of neutron-rich fragments produced by fissions of heavy elements, such as Uranium and Plutonium. On an average, a single fission event is followed by the production of approximately six antineutrinos. For the nuclear reactor Dhruva at BARC, which operates at a power of 100 MWth, the antineutrino flux emitted is $\sim 1.5\times 10^{19}$ antineutrinos / second. The large emitted flux allows the detection of the antineutrinos, even though, the interaction cross section between matter and neutrinos is very small ($\sim 10^{-43}$ cm^2). In this work, we present the simulation results of a prototype detector for the detection of antineutrino events. The detector that is modeled consists of 3 ×4 plastic scintillator arrays, each having a dimension of 100 cm × 6 cm × 6 cm. This geometry is same as the prototype setup that has been used for the initial background measurements at the Dhruva reactor [2]. Each scintillator bar is wrapped with gadolinium (Gd) coated Mylar films (4.9 mg/cm^2) and readout on two sides by photomultiplier tubes. We focus on the path length, multiplicity, efficiency, energy response and the neutron capture time spectra produced in the detector array due to the antineutrino interactions.

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Detection Principle

Antineutrinos from the reactor interact with protons in the plastic scintillator bars, via the Inverse Beta Decay (IBD) reaction

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

The positron which carries most of the energy rapidly loses its energy via ionization in the detector and gets annihilated producing two gamma rays. The positron constitutes the prompt signal along with the Compton scattered annihilation gamma rays. The energy of prompt signal is given by

$$E_{prompt} = E_{\bar{\nu}_e} + Q + 2m_e c^2, \quad (2)$$

where, $E_{\bar{\nu}_e}$ is the energy of antineutrino and Q-value equals -1.80 MeV. This prompt pulse is followed by a delayed signal, which arises due to the radiative capture of the thermal neutron mostly in Gd, which produces a cascade of gamma rays with total energy $\sim$ 8 MeV. The IBD event is distinguished from the background using the correlation between the prompt and the delayed signals.

Simulation and reconstruction

To study the performance of the detector, the object oriented simulation toolkit GEANT4 [3] has been used for the detailed simulation of detector array. The positron and neutron are produced which are generated due to $\bar{\nu}_e$ interactions occuring in the detector. A sample of 10^5 events with energies up to 10 MeV are randomly generated and propagated within the detector volume. A typical event propagation in the detector is shown in Fig. 1. The positron is captured close to the vertex position and produces two annihilation gammas. Neutron is captured at the boundary in the Gd -foil producing gammas some of which undergo multiple Compton scattering in the detector and lose their energy.

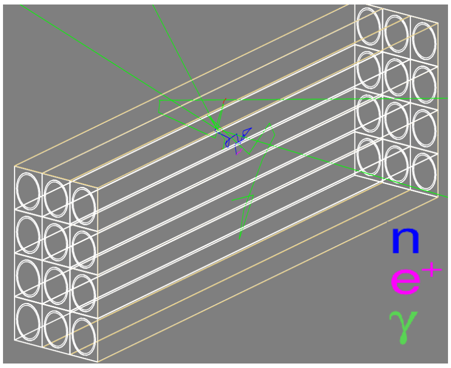

FIG. 1: View of a typical event propagation in the detector array

Results and Discussions

The multiplicity of gamma rays produced by neutron capture and positron annihilation for 20000 events with optical processes included in GEANT4 is shown in Fig. 2 at energies of 10 keV for the neutron and 3 MeV for the positron. The average multiplicity for the gamma rays is found to be equal to four. Fig. 3 shows the distribution of path length displacement for the neutron traversed in the detector array for 10^5 events. It is estimated by considering the events in which neutrons are captured inside the detector. It is found that the mean distance travelled in the detector by neutron before its capture in Gd foil is about 6 cm. Similarly, the path length of positron is calculated considering the events that produce annihilation gamma rays within the detector and it is shown in Fig. 4. The average distance traversed by positron before its annihilation is about 1 cm. The detector efficiency is $\sim$ 60% for the neutron capture and $\sim$ 95% for the positron annihilation in the detector. From the simulation, it can be concluded that positron can be detected with very high efficiency within a single scintillator bar while the neutron can be detected with $\sim$60 % efficiency in few neighbouring bars. Detailed simulation studies using the prototype and final detector setup is in progress.

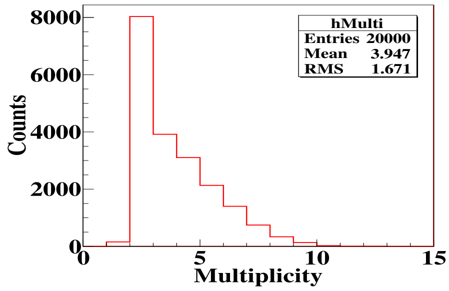

FIG. 2: Multiplicity distribution for the gamma rays

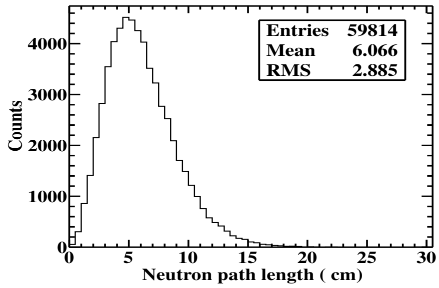

FIG. 3: Neutron path length in the detectors array

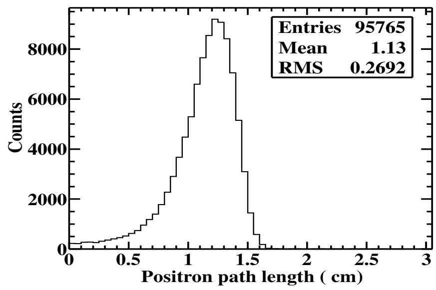

FIG. 4: Positron path length in the detectors array

References

[1] S. Oguri et al., arXiv:1404.7309.
[2] V. K. S. Kashyap et al., Proceedings of this symposium.
[3] https://cern.ch/geant4.