Indian Scintillator Matrix for Reactor Anti-Neutrino detection

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Abstract. Indian Scintillator Matrix for Reactor Anti-Neutrino (ISMRAN), made of an array of plastic scintillator bars, has been proposed for the remote monitoring of the nuclear reactor by using anti-neutrinos ($\bar{\nu}_e$). The proposed experiment will be housed in Dhruva reactor at Bhabha Atomic Research Centre, Mumbai, India. In this talk, we present the progress and status of the ISMRAN project and will discuss the results related to the gamma and neutron background measurements at the reactor hall. We will also present the preliminary estimates of the feasibility of this project at Dhruva reactor.

1. Introduction

Nuclear reactors are one of the major sources which produces electron anti-neutrinos ($\bar{\nu}_e$). Techniques for the detection of these $\bar{\nu}_e$ for remote monitoring of the reactor are being pursued actively by many groups across the world [1, 2, 3, 4]. Active physics programs are also being pursued with these detectors for the better understanding of the reactor $\bar{\nu}_e$ anomaly and oscillation measurements in the neutrino physics sector [5, 6]. In this talk, we will present the status and progress of the Indian Scintillator Matrix for Reactor Anti-Neutrino (ISMRAN) project at Bhabha Atomic Research Centre. The main goal of this program is to establish the measurement technique of the reactor $\bar{\nu}_e$ using a matrix array of plastic scintillators. We will also present the details of the gamma and neutron background measurements at reactor experimental hall which would help us in optimizing the shielding and estimating the accidental rates for the ISMRAN detector. A preliminary results from a Monte-Carlo based simulation of various shielding materials will also be discussed.

2. ISMRAN detector

The proposed ISMRAN detector [7] at Dhruva reactor will consist of a $10 \times 10$ array of 100 plastic scintillator bars of dimension 10cm $\times$ 10cm $\times$ 100cm. The detector active volume is 1 m$^3$ and is equivalent to the 1 ton by weight. Each plastic scintillator bar is wrapped with Gadolinium (Gd$_2$O$_3$) coated mylar foils. The concentration of Gd$_2$O$_3$ in the foils is 4.8 mg$^{-2}$. Each
bar is coupled to two $3''$ photomultiplier tubes at opposite ends along the length. The proposed distance of ISMRAN from the reactor core is 13 m and resides on the ground level. Figure 1 shows a typical plastic scintillator bar of ISMRAN detector. Figure 2 shows the schematic of the proposed full scale ISMRAN detector. The core detector which comprises of the plastic scintillator bars will be inside a 10 cm thick Lead (Pb) and 10 cm Boronated polythene shielding for the reduction of the gamma and neutron background. A set of muon veto scintillators will be covering the six planes from the outside of shielding to reject the cosmic muon triggered events inside the plastic scintillator detector active volume. $\bar{\nu}_e$ will interact with the scintillator volume in ISMRAN through the inverse beta decay producing a positron and a neutron. Most of the energy of the $\bar{\nu}_e$ will be carried by the positron. The prompt signal will comprise of the kinetic energy deposited by positron and two 0.511 MeV gammas after its annihilation in the detector. The neutron would eventually thermalize in the active volume of the detector and would be captured by the Gadolinium. The cascade of gamma rays, coming from the de-excitation of the Gadolinium, forms the delayed signal. The number of $\bar{\nu}_e$ detected by a detector can be estimated using the formula:

$$N_{\bar{\nu}_e} = \frac{N_p \eta t P_{th} \bar{\sigma}_{p-\bar{\nu}_e}}{4\pi D^2 E_f},$$

where $N_p$ are the number of quasi-free protons ($=5.23 \times 10^{28}/m^3$), $\eta$ is the detector efficiency ($\sim30\%$) and $t$ the time duration of data taking period. The detector is assumed to be at a

**Figure 1.** One plastic scintillator bar of dimension $10\text{cm} \times 10\text{cm} \times 100\text{cm}$, wrapped with Gadolinium foil, with $3''$ photomultiplier tubes at ends.

**Figure 2.** ISMRAN detector design with 10 cm Lead (Pb), 10 cm Boronated Polythene (BP) shielding and muon veto scintillators.

**Figure 3.** Percentage of events, from Geant4 simulations, entering the Pb and Boronated Polythene shielding.
distance of $\sim$13 m from the reactor core and the thermal power ($P_{th}$) is taken as 100 MW. The flux average cross-section $\bar{\sigma}$ is taken as $5.91 \times 10^{-43}$ cm$^2$ and the average energy per fission $\bar{E}_f = 204.7$ MeV. The expected anti-neutrino rate in ISMRAN with the above mentioned inputs is $\sim 115$ per day. These numbers were obtained by assuming a point source in the above calculation. For an extended source the expected rate should increase slightly. We have performed Monte-Carlo based simulations using Geant4 [8] for optimizing the Pb and BP thickness for the detector. Figure 3 shows the accepted percentage of events which would penetrate different shielding thickness for various incident gamma and neutron energies. With the 10 cm of Pb and 10 cm of BP shielding the background events reduces to $\sim 2\%$ for gamma upto 10 MeV of incident energies. For neutrons, the accepted events inside the active volume of the ISMRAN detector is around 10$\%$ for 1MeV of incident neutron energies.

3. Gamma and Neutron measurements at ISMRAN

The gamma and neutron background measurements were performed using various detectors. A Bismuth Germanium Oxide (BGO) detector and a plastic scintillator bar (6cm $\times$ 6cm $\times$ 100cm) was used to measure gamma background in reactor ON and OFF condition. The enhanced gamma background in the BGO, shown in Fig. 4, as well as in plastic scintillator bar, shown in Fig 5, are observed in reactor ON conditions. This enhancement in the gamma background is from the neutron capture on surrounding material which consists of iron, carbon and oxygen. The background rate reduction in reactor ON condition using a smaller bar with Pb and BP shielding is summarized in Table 1.

| Reactor Power (85MW) | Count rate (Hz) |
|----------------------|-----------------|
| No shielding, single bar (2 PMT coincidence) | 30,000 |
| 10 cm Pb, single bar (2 PMT coincidence) | 2,000 |
| 10 cm Pb, 2 bars (4 PMT coincidence) | 300 |
| 10 cm Pb + 1 cm BR, 2 bars (4 PMT coincidence) | 70 |

The thermal neutron measurements were done using Lithium Yttrium Borate ($\text{Li}_6\text{Y(BO}_3)_3 : \text{Ce(0.2\%)}$) (LYBO) crystal developed by Technical Physics Division, BARC. Measurement at
reactor hall were carried out with and without the boronated rubber (BR) shielding. Figure 6 shows a peak due to neutron capture on $^6Li$. By wrapping the crystal with BR, thermal neutron yield is reduced by a factor of 3. Lead was used to shield the detector from the ambient gamma background. For fast neutron background measurements we used a 5″ NE213 liquid scintillator detector coupled with photomultiplier. The neutron and gamma were separated by using pulse shape discrimination (PSD) technique. Integrated charge of the signal pulse in the short ($Q_S$) and long ($Q_L$) gates in time were used to obtain the PSD parameter ($PSD = 1 - Q_S/Q_L$). Figure 7 and Fig. 8 shows the PSD variable as a function of energy ($MeV_{ee}$) with and without Pb+BR shielding in reactor on conditions, respectively. The yield for fast neutrons and gammas are reduced with the Pb+BR shielding in the reactor on condition. To quantify this reduction we study the differential rate over the period of time for the neutrons and gamma separated from the PSD technique. Figure 9 shows the neutron and gamma yields with different energy thresholds applied on the detector. The gamma and neutron rates with minimum threshold ($0.12 \ MeV_{ee}$) on the detector in reactor on condition are $\sim 10$ Hz and $\sim 100$ Hz, respectively. This reduces to $\sim 0.1$ and and $\sim 40$ Hz in the reactor off condition. The use of higher threshold ($2-3 \ MeV_{ee}$) leads to a reduction by factor of $>100$ for dominant gamma background. For the ISMRAN detector, discrimination of gamma and neutron is not possible. Based on the values measured as shown in table 1, scaled to appropriate geometric dimension of the actual bar ($10cm \times 10cm \times 100cm$), a single bar background coincidence rate of $\sim 5 \ kHz$ is expected. For a 20 scintillator array, this would lead to a random coincidence rate $\sim 240 \ Hz$, in pair of bars with an assumed time window $\tau=50 \ ns$ for both prompt and delayed signals. Assuming a reduction

**Figure 6.** Thermal neutron yields from the LYBO crystal irradiated in reactor with only Pb shield (red) and with Pb and borated rubber (black) sheets. A factor of 3 $\times$ reduction of yield of thermal neutrons is observed when the crystals were covered with borated rubber sheets.

**Figure 7.** PSD as a function of deposited energy from NE-213 liquid scintillator detector without shielding in reactor ON condition.

**Figure 8.** PSD as a function of deposited energy from NE-213 liquid scintillator detector with 10 cm Pb and 1 cm BR shielding in reactor ON condition.
factor of $>100$ for 2 to 3 MeV threshold on the delayed signal and a reduction of factor of $\sim 10$ for the prompt signal with cuts due to small thresholds and event topology, we expect a background rate of $\sim 500$ per day within prompt-delayed time difference of 100 $\mu$s. With current detection efficiency assuming a signal of 10 $\bar{\nu}_e$s per day, a detection sensitivity of 3$\sigma$ level can be obtained in 40 days of measurement, which can be reduced to 10 days with a four times better suppression of background with optimized closed shielding of the active detector volume.

4. Summary
The Indian Scintillator Matrix for Reactor Anti-Neutrino (ISMRAN) is being actively pursued at BARC Dhruva reactor facility. The proposed detector would be at ground level at a distance of 13 m from reactor core. The detector consists of plastic scintillator bars of 100 bars of dimension of 10cm$\times$10m$\times$100cm to form a 1 ton detector by weight. The design of the multi-layered shielding is in process and detailed simulations are in progress. Initial measurements for neutron and gamma backgrounds are performed at reactor hall with various detectors and the background rates were estimated for reactor ON and OFF conditions. A complete data acquisition system based on CAEN based waveform digitizers is being developed and tested for the final experimental setup. To reach a 3$\sigma$ level sensitivity for reactor monitoring, a measurement of 40 days in reactor ON condition is expected with a 20 bar setup.

5. Acknowledgments
We would like to thank personnel from Reactor Operations Division and Research Reactor Services Division, BARC for providing us the opportunity in conducting necessary measurements at Dhruva reactor hall. We would also like to thank our colleagues from Technical Physics Division for providing us with the LYBO crystal for thermal neutron measurements. Our sincere thanks to A. Bernstein and N. S. Bowden for the academic discussions on the ISMRAN detector project.

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