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Angular distribution of cosmic muons using INO–ICAL prototype detector at TIFR

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Abstract. The India-based Neutrino Observatory Collaboration is planning to set up a magnetized 50 kt iron calorimeter (ICAL) with resistive plate chambers (RPC) as active detectors to study neutrino oscillations and precisely measure its parameters. A prototype detector stack is set up at TIFR (18°54′N, 72°48′E) to track cosmic ray muons. Using the muon data, angular distribution of cosmic ray muons at the sea level is studied here.

Keywords. India-based Neutrino Observatory; cosmic ray muons; flux.

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1. Introduction

The India-based Neutrino Observatory–iron calorimeter (INO–ICAL) is a proposed neutrino physics experiment in India. Resistive plate chambers (RPCs) are chosen as active detectors in ICAL. The prototype detector stack, functional at TIFR, comprises 12 layers of glass RPCs of $1\,\text{m}\times 1\,\text{m}$ area, without being interleaved by any iron plates. Detector performances are well-studied using cosmic ray muons. In parallel, cosmic ray muon flux at sea level (integrated over all available energies) is also measured using this detector set-up.

The general form of cosmic ray muon flux at sea level is assumed as $I = I_0 \cos^n \theta$ ($\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$), where θ is the zenith angle of the incident particle to the detector and I_0 is the vertical cosmic muon flux integrated over available energies at sea level. The best-fit values of I_0 and n which follows the data are presented here. A comparison with other existing measurements is also discussed.

2. Detector set-up

A brief description of the detector set-up is given below:

Geometrical set-up: Twelve layers of RPCs are stacked on top of each other, separated by a distance of 16 cm which amounts to a total stack height of 1.76 m. Each RPC in this cosmic ray stand has 32 strips on either side of the read-out planes labelled as X and Y, with the strip in the X plane orthogonal to the strips in the Y plane. The width of the strip is 2.8 cm and the gap between adjacent strips is 0.2 cm.

Experimental set-up: A detailed description of DAQ and signal processing are explained in refs [1–3]. Trigger condition of $4/12$ layers coincidence is used to record valid cosmic muon events. Here, 2, 4, 7 and 9 layers are used in trigger criteria. This particular choice helps to increase the detector solid angular acceptance.

3. Event data analysis

Event data consist of two informations: (i) cosmic ray muon hits per layer and (ii) the corresponding time of arrival. Here, hit information is only used to get the angular distribution of muons. Average cluster size is around 1.6 strips per layer; but outliers are present in the hit pattern arising mainly due to correlated electronic noise [3]. Therefore, data reduction becomes necessary before fitting. X-side and Y-side data are fit separately. A maximum of three consecutive strip hits per layer (on either side) is considered as real cosmic ray muon signal. The average of these hits is finally used for track fit. This criterion selects ∼97% of the total recorded events.

Selected hit points are linearly fitted and a hit point is rejected if the fit residual is greater than one strip width and another fit is performed with the remaining hits. An event is accepted if its X and Y side fit together satisfy these cuts: (i) at least four layers of data are present in fitting and (ii) fit $\chi^2/ndf < 2$. This event track selection criterion accepts ∼75% of the selected events.

The zenith angle of the cosmic ray muon is obtained from the fit results from which $dN^{obs}/d\theta$ is estimated.

4. Monte-Carlo event generation

Monte-Carlo events are generated (using uniform random number (0–1)) to calculate detector acceptance or detector differential aperture with the specified trigger condition. Hit points for the 9$^{\text{th}}$ layer, (x_9, y_9), are generated first. The direction of the track is fixed through the zenith angle (θ) and the azimuthal angle (ϕ). θ is generated uniformly over the solid angle and ϕ over the 0–2π range. Using these, (x_2, y_2) is obtained and then hit points for other remaining layers are obtained. These hits are then smeared following layer offset, digitization effect and hit multiplicity effect like data. Every hit is selected by following the pixel efficiency profile per layer from the real data without allowing uniform weight for every pixel. These hits are linearly fitted afterwards. Same event selection criteria are used as discussed in §3. The zenith angle distribution here gives the detector differential aperture under proper normalization.

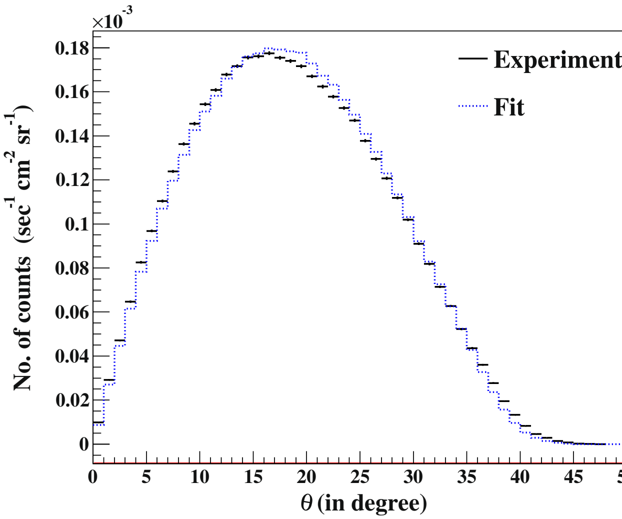

Figure 1. The flux distribution (black points with error bar) and the fitted distribution (dotted blue line).

5. Results

The χ^2 definition for the statistical minimization procedure is as follows:

$$\chi^2 = \sum_{\theta=0}^{\theta_{\max}} (N_\theta^{\text{obs}} - I_0 \cos^n \theta \times w_\theta)^2 / N_\theta^{\text{obs}}. \tag{1}$$

N_θ^{obs} is the count for a particular θ bin and w_θ is the corresponding weight factor for the differential aperture for that θ bin. Normalized observed muon flux distribution along with the fit is shown in figure 1.

The best-fit values of the two parameters are: $I_0 = (0.526 \pm 0.001) \times 10^{-2}$ cm^{-2} s^{-1} sr^{-1} and $n = 2.385 \pm 0.018$.

The cut-off momentum of the cosmic ray muon due to roof, glass, aluminium and polycarbonate electronic read-out panel is around 280 MeV/c. Existing results of ref. [4] show I_0 for this momentum cut-off to be about 0.845×10^{-2} cm^{-2} s^{-1} sr^{-1}. Other existing results [5–7] vary from $\sim$0.7 to 0.9×10^{-2} cm^{-2} s^{-1} sr^{-1}, depending on different latitudes and minimum momentum cut-off.

6. Conclusion

The measured value for the vertical cosmic muon flux is less than what was obtained earlier in ref. [4]. Work is currently in progress to understand this deficit in the measured flux.

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