



## Response of IceTop tanks to low-energy particles

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**Abstract:** Solar activity can cause variations in the cosmic-ray particle flux measured at the Earth's surface. This manifests mostly in the low-energy electromagnetic component of cosmic ray induced cascades. The IceTop experiment detects these particles by their emission of Cherenkov light in a contained ice volume through photo-multipliers. We give the prediction of the response to the low-energy part of cascades and compare to experiment.

## Introduction

The IceTop Air Shower Array, located close to the geographical South Pole (altitude 2835 m, 700g/cm<sup>2</sup>), consists of tanks with reflective liners using clear ice as a Cherenkov medium. Light generated in the ice is observed by digital optical modules (DOMs) which consist of a photo multiplier tube (PMT) and digitising electronics assembled in a glass pressure sphere. Thus, energy deposition of particles can be measured through the observed light yield. Each tank has two DOMs running at different gain settings to increase the dynamic range of the observations. Two tanks, placed at 10 metres from each other, are combined into a station. Currently, 26 stations, separated by typically 125 metres, forming a diamond shaped triangular grid are deployed. In normal operation, the high gain DOMs are run in coincidence to reject events not associated with air showers. For this work, we use data from tanks run in "single mode", in which the coincidence condition is disabled.

## Simulations

Two separate simulations are utilised in this analysis, one based on CORSIKA[1] and another on FLUKA/AIR[2, 3].

**In the AIR model,** primary protons, alphas, carbon, silicon and iron are generated within the rigid-

ity range of 0.5GV-20TV uniform in  $\cos^2(\theta)$ ,  $\theta$  being the zenith angle. The atmosphere density profile (23.3% oxygen, 75.4% nitrogen and 1.3% argon) was based on the US Standard Atmosphere 1976 model. The primary cosmic ray spectrum used in this calculation was determined through an analysis of simultaneous proton and helium measurements made on high altitude balloon flights (see refs. in [3, 4]). The outer air-space boundary is radially separated by 65 kilometres from the inner ground-air boundary and a single 1 cm<sup>2</sup> element on the air-space boundary is illuminated with primaries. Particle intensity at various depths is determined by superimposing all elements on the spherical boundary defining the depth. Due to rotational invariance this process is equivalent to illuminating the entire sky and recording the flux in a single element at ground level. Although this approach provides a quick result, it ignores the effects of multiple particle tracks entering the IceTop tanks simultaneously.

**In the CORSIKA simulation,** the hadronic interaction model for energies above 80 GeV is SIBYLL v2.1[5], for lower energies FLUKA is applied. The electromagnetic interactions are treated with EGS4[6]. Hydrogen as well as helium primaries are simulated with angles between 0 and 70 degrees. The angular spectrum is constant in  $\cos^2(\theta)$ , like for the AIR simulation. The cascades are generated with primary energies between 10 GeV and 468 GeV with a power-law  $\sim$

$(E/E_0)^{-1}$  and are re-weighted later to the fluxes averaged from various experiments[4]. Two atmospheres for the austral winter and summer (1st of July/31st of December) parametrised by the MSIS-90-E model[7] are used. We find that the counting rate in the austral winter is approx. 6% higher compared to the summer. In a second step, the cascade particles are inserted into the detector simulation to generate the light yield in the photo multiplier. The simulation is based on GEANT4[8] and takes into account the interactions of particles and the tracking of the Cherenkov photons. This requires input of the optical parameters of the inside of the tank. The reflectivity of the tank liner was measured as a function of wavelength in the laboratory. The first eight tanks of the experiment are lined with Tyvek<sup>TM</sup>, while the later tanks have an integrated coating using zirconium as reflective agent. The simulations are done using the optical properties of the Tyvek<sup>TM</sup>liner.

The tank is then modelled as a cylindrical polyethylene vessel of 0.93 metre radius and 1.00 metre height, filled with ice to a level of 0.90 metres. The tank is embedded in 0.3 metres of snow, simulated as water of density  $0.4 \text{ g/cm}^3$ . Regarding the optics of the ice, a refractive index of 1.33 is assumed and the absorption length is set to 200 metres, based on measurements in the deep glacial ice and on comparisons of the simulations to the experimental data. The ice is covered with  $47 \text{ g/cm}^2$  of Perlite<sup>TM</sup> which is modelled as opaque to light but reflective at the ice interface. The light propagation in the DOM itself is simulated using the geometry and optical properties of the pressure sphere, the PMT glass and the optical gel coupling the two. The quantum efficiency of the photo cathode is applied to yield individual photo electrons. However, neither the amplification stages nor the signal processing electronics are simulated. The final result of the simulation is the number of photo electrons (npe).

## Secondary particle spectra

The resulting secondary particle spectra from simulation and experiments[9] are shown in Fig. 1. All measurements of the electrons, muons and gammas took place at solar minimum and a low geo-

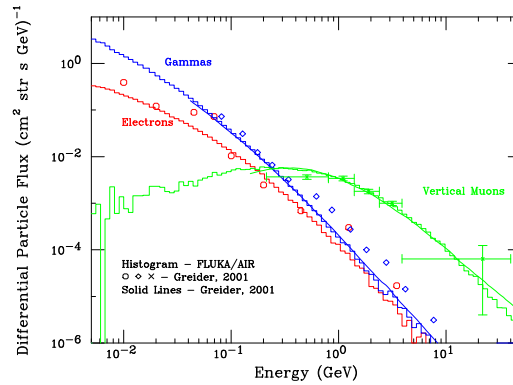


Figure 1: Fluxes of secondary electrons, muons and gammas from simulation for solar minimum, compared to experiments compiled in[9].

magnetic cutoff, comparable to South Pole conditions. The muon and electron measurements were made by a balloon instrument while the gamma rays were measured from a mountain top. The agreement with the simulations is reasonable, however the differences will be investigated.

## Response to electrons, muons and gammas

The particles entering the tank are detected by the DOM either by their own Cherenkov light (if they are charged) or by the light emitted in stochastic processes (pair production, delta electrons, etc.). The number of photo electrons seen per particle

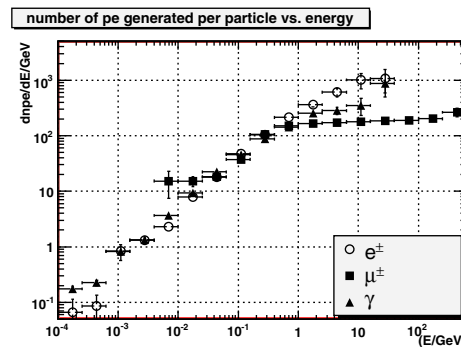


Figure 2: Number of photons per particle vs. particle energy.

as a function of the particle energy in the tank is shown in Fig. 2. It is averaged over all angles and

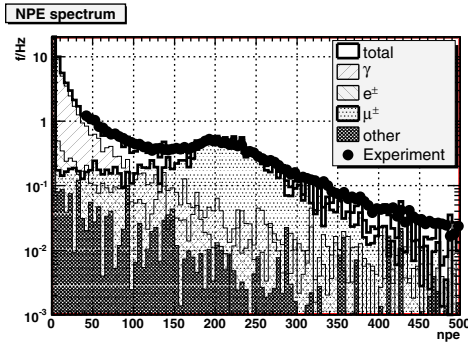


Figure 3: Contribution of secondary particles to the overall npe signal. The experimental data for DOM 63 of station 29's Tyvek<sup>TM</sup> lined tank is shown as well.

impact parameters. The light yield of the muons turns flat at around 1 GeV, where the muons become minimal ionising plus a logarithmically rising stochastic contribution. For all three particle types, the light generation threshold is around 1 MeV.

### Contributions to the photon electron rate

The simulation allows one to study the contribution of the different cascade secondary particles to the photo electron response from the DOM. This is shown in Fig. 3. For different particles (gamma, electron, muon and other), the number of photons seen by the DOM is summed up and histogrammed.

The dominant contributions come from gammas, electrons and muons, however the neutron component is significant at low primary energy. Other particles contribute at the 1% level.

The simulation is compared to measurements. There are some variations in the position of the muon peak from tank to tank and a tank fitting the simulation is shown. Since the purpose of these data is to determine the position of the muon peak, a threshold of about 40 npe is applied. There is good agreement between experiment and simulation.

### Primary Cosmic Ray Single Mode Ice-Top Yield Function

The yield function  $S(P, z)$  describes the primary cosmic ray detection efficiency of a full sky illumination of particles averaged over all arriving angles (uniform in  $\cos^2(\theta)$ ). It is related to the count-rate  $N(P_C, z, t)$  by

$$N(P_C, z, t) = \int_{P_C}^{\infty} (S(P, z) j(P, t)) dP.$$

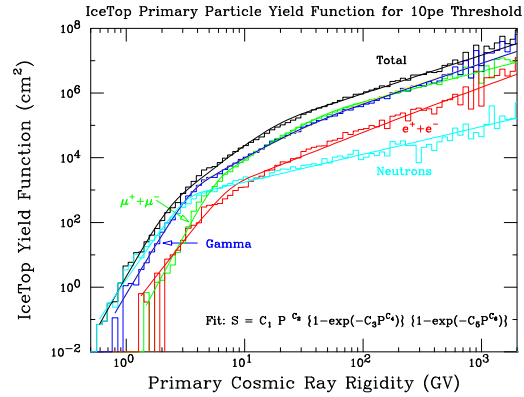


Figure 4: Primary cosmic ray yield function  $S(P, z = 700\text{g/cm}^2)$  for IceTop tank in singles mode. The individual contributions made by secondary components to the yield function are separated into different curves.

where  $P$  is the particle's rigidity (momentum/charge),  $z$  is the atmospheric depth and  $t$  represents time.  $P_C$ , the geomagnetic cut-off, is effectively 0 at the South Pole. Using  $S_i(P, z)$ , the single mode IceTop yield function, and  $j_i(P, t)$ , the primary rigidity spectrum for primaries of particle type  $i$ , one can decompose the product of yield function and rigidity spectrum,  $S(P, z) j(P, z)$  into  $\sum S_i(P, z) j_i(P, z)$ . Utilising the FLUKA/AIR model and a FLUKA Cherenkov optical model assuming a zirconium lined IceTop tank, the IceTop yield function was calculated for a 10pe threshold (Fig. 4). The data are fit using a variation of the Dorman Function[10]

$$S(P) = C_1 P^{C_2} \times (1 - \exp\{-C_3 P^{C_4}\}) \times (1 - \exp\{-C_5 P^{C_6}\}),$$

typically used to model Neutron Monitor latitude survey data. The fit parameters extracted from the simulations in Fig. 4 are shown in Tab. 1.

| $C$ | Total   | Muons   | Gammas  | $e^+ + e^-$ |
|-----|---------|---------|---------|-------------|
| 1   | 4024.2  | 6800.8  | 1433.8  | 1964.9      |
| 2   | 1.1887  | 0.9467  | 1.2525  | 1.0620      |
| 3   | 7.90E-3 | 4.73E-3 | 4.95E-2 | 3.85E-2     |
| 4   | 1.7910  | 1.5179  | 0.9900  | 0.4186      |
| 5   | 6.93E-2 | 6.06E-4 | 8.83E-3 | 1.86E-3     |
| 6   | 3.5573  | 4.3684  | 3.9344  | 3.2784      |

Table 1: Fit values for the yield function

## Integral count rates

The above information can now be used to predict counting rates above a given threshold (Fig. 5). The agreement between experiment and simulation is reasonably good for the solar minimum and

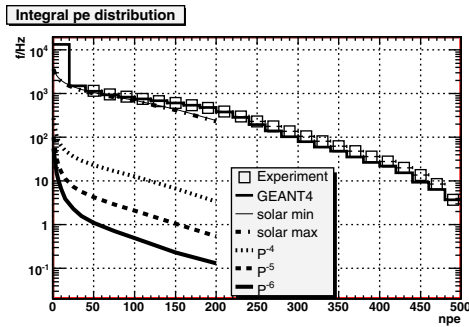


Figure 5: Integrated photon counting rates for various primary spectra, including  $P^{-4,-5,-6}$  as expected for solar activity. Note that solar minimum and maximum give approximately the same rates.

maximum periods. For the  $P^{-4,-5,-6}$  spectra, which are expected for solar flares, the counting rate is expected to drop by 2-3 orders of magnitude.

## Conclusion

The IceTop tanks are sensitive to low energy particles produced in cascades by cosmic radiation. The response of the IceTop detectors is understood reasonably well in terms of the simulation,

as shown by comparison to experimental measurements. This allows predictions of rate changes induced by changes in the primary particle spectrum. We expect count rate drops beyond variations induced by atmospheric variations, leading to good detectability of solar events.

This analysis ignores the effects of multiple particle tracks entering the IceTop tanks simultaneously as each particle track reaching the ground is treated as an uncorrelated event regardless of arrival time. For low energy primaries this is a valid approach, however at high energies this could be a source of systematic errors. This effect will be investigated in order to quantify it.

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## References

- [1] D. Heck et al., Report FZKA 6019, Forschungszentrum Karlsruhe
- [2] A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC\_05/11, SLAC-R-773
- [3] J. M. Clem, G. De Angelis, P. Goldhagen, and J. W. Wilson, Radiat. Prot. Dosimetry, 110: 423-428, 2004.
- [4] T.K. Gaisser, M. Honda, P. Lipari, and T. Stanev, Proceedings of ICRC (2001) 1643
- [5] R.S. Fletcher, T.K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D50 (1994) 5710
- [6] W.R. Nelson, H. Hirayama, and D.W.O. Rogers, Report SLAC 265 (1985), Stanford Linear Accelerator Centre
- [7] <http://nssdc.gsfc.nasa.gov/space/model/atmos/msise.html>
- [8] Geant4 Collaboration, NIM A 506 (2003), 250-303
- [9] Peter K.F. Grieder, Cosmic Rays at Earth, Elsevier, 2001
- [10] J. M. Clem, and Lev I. Dorman, Space Science Rev., Vol 93., p. 335-359, 2000