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Fluxes of Hadrons, Muons and Electromagnetic Components at the Mountain Altitude induced by Hadrons in the Atmosphere with Energies between 100MeV and 1000 GeV

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Abstract: A large number of solar protons are accelerated into high energies by solar flares. They are observed as Ground Level Enhancements (GLEs). In previous cosmic ray conferences the percentage increase of cosmic rays induced by solar flares was reported. This was sufficient to describe briefly the effect of solar flares at Earth. However, a problem is encountered if we wish to describe the energy spectra of protons at the Earth. Particle detectors are commonly located at different places on the world, and at different altitudes. The attenuation of neutrons and protons in the atmosphere is therefore different from one detector to another. Corrections need to be made to account for these differences in order to determine energy spectra. Monte Carlo calculations performed by Shibata provided atmospheric attenuation curves for neutrons with energies from 50 MeV to 1 GeV. In this paper, we employ the GEANT 4 and CORSIKA Monte Carlo simulation codes to obtain correction data for the analysis of Solar Energetic Particles (SEPs) with energies in the range 100MeV to 1000GeV.

Purpose of Monte Carlo simulation

Large numbers of particles are accelerated to high energies in solar flares, sometimes beyond 10 GeV. These particles reach Earth and produce Ground Level Enhancements (GLEs). They used to be monitored by the GOES satellite. When we try to deduce the energy spectra of SEPs at the top of the atmosphere, it is necessary to combine data obtained by the GOES satellite with data obtained by neutron monitors at ground levels. A conversion factor of the neutron monitor data is then needed to deduce fluxes at the top of the atmosphere. Neutron monitors are sited at various altitudes observations are often made at different altitudes. Atmospheric attenuation factors of SEPs at various altitudes are therefore required. A good code of Monte Carlo calculations was not made available until recently. This is because the interaction processes of very low energy neutrons in nuclear cascades are complicated. However, the new GEANT 4 code (version 4.6.2.p02) together with the interaction model, QGSP_BERT [1], is now available with improved simulations of neutron cascade processes at low energies down to a few MeV. It is now possible to deduce initial proton fluxes at the top of the atmosphere with use of these codes.

In this paper, we present new results on atmospheric attenuation and compare these with results calculated by CORSIKA. The new results should be useful in future cosmic ray research, especially for understanding SEPs. A valuable catalogue of SEPs was published by Moscow University Press in 1998 [2]. In addition, they were summarized in two books on cosmic rays [3, 4].

Conditions of calculations and Results

We calculated integral spectra of electrons, photons, muons, protons and neutrons for primary incident protons and neutrons with energies 10, 50, 100, 500, and 1000 GeV respectively. The power indices of proton and neutron primaries were both assumed to be -2.5 above 1 GeV. The calculations were made using CORSIKA and GEANT 4 independently, and examined for consistency. Typical results for electrons are shown in Fig. 1, for photons in Fig. 2, for negative muons in Fig. 3, for neutrons in Fig. 4, and for protons in Fig. 5, at an atmospheric depth of 600g/cm2.

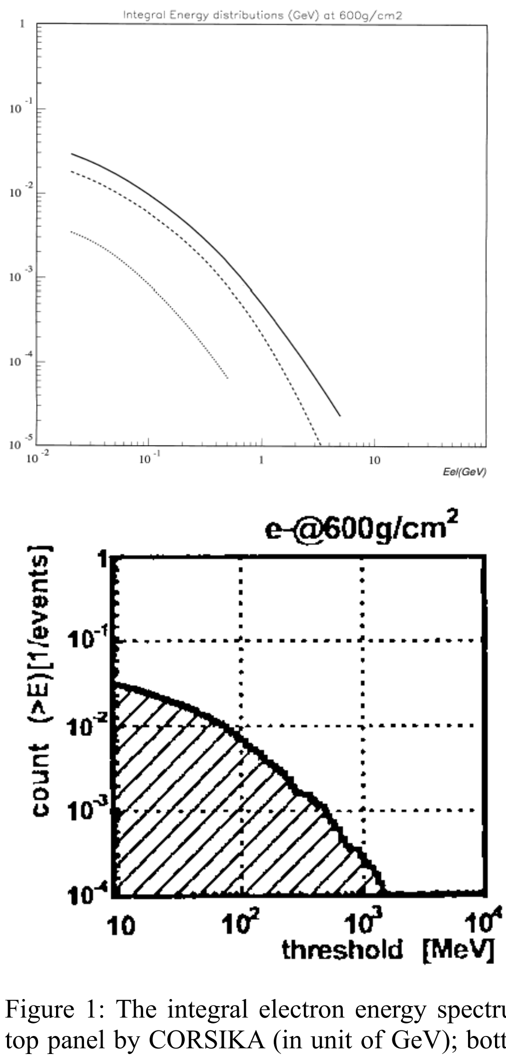

Figure 1: The integral electron energy spectrum: top panel by CORSIKA (in unit of GeV); bottom panel by GEANT 4.

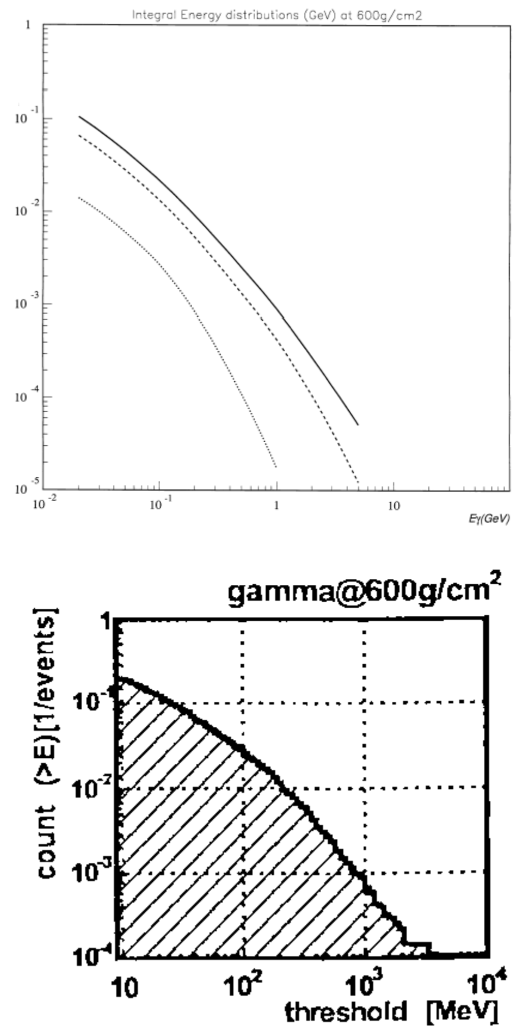

Figure 2: The gamma-ray energy spectrum: top panel by CORSIKA and bottom panel by GEANT 4.

The results shown in Figs. 1 and 2 demonstrate good consistency between the CORSIKA and GEANT4 codes. These results are reassuring. When comparing the results on neutrons, the integral spectrum with GEANT 4 was obtained for the primary neutrons with energy En= 1-100 GeV and power index -2.5. These results should be compared the central CORSIKA curve in the upper panels of Figs. 1-5. Note that the observation altitude was set at 600 g/cm2, and that the plots were obtained for vertically incident neutrons. For the photon component, the GEANT 4 code predicts a slightly higher value than CORSIKA in the energy region $E\gamma < 100$ MeV than the CORSIKA, i.e., the energy spectrum is consistent with the solid curve of Figure 2 for primary neutrons with En= 1-1000 GeV. Further investigation is necessary on this point.

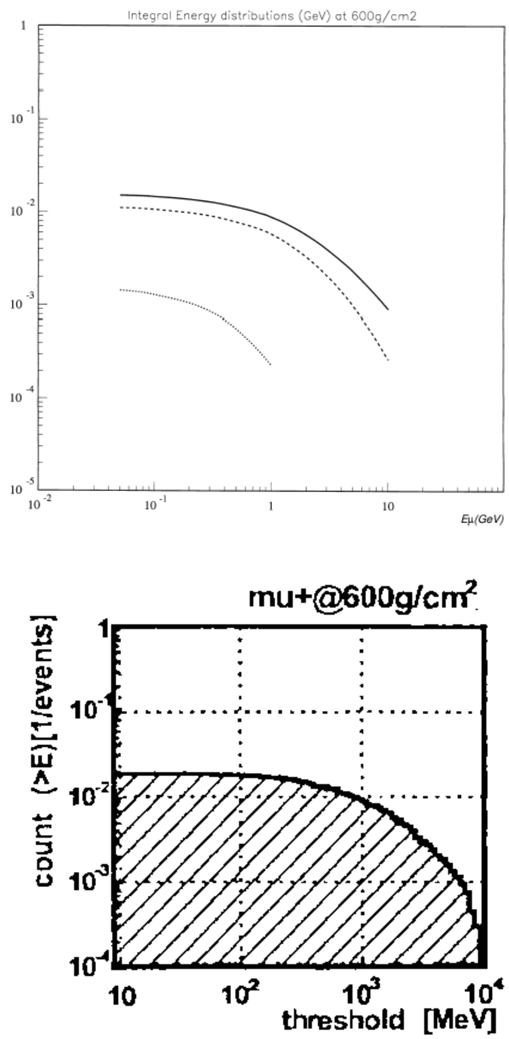

Figure 3: The negative muon spectrum:top panel is calculated by CORSIKA and bottom panel by GEANT 4.

The upper lines of CORSIKA panels (solid line) represent for the contribution of primary neutron components with En= 1-1000 GeV, the middle line (dashed) for En= 1-100 GeV and the lower line (dotted) for only the contribution of neutrons with En=1-10 GeV. For muons, a very good coincidence of the numerical results has been obtained.

Hadron Component

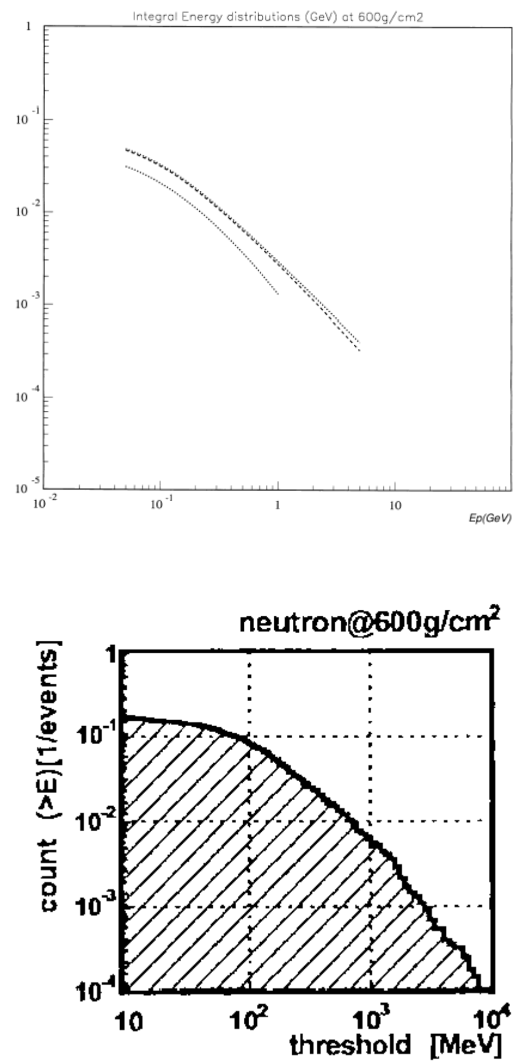

Figure 4: The neutron spectrum: top panel is calculated by CORSIKA and bottom panel by GEANT 4. Here the notation of the horizontal axis of the top panel should be read as $E_{neutron}$.

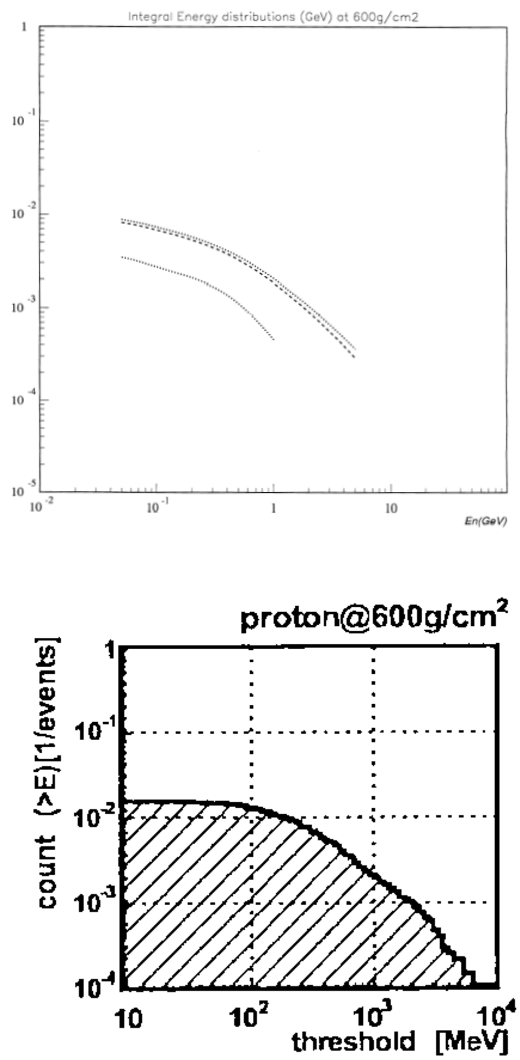

Figure 5: The proton energy spectrum: top panel is calculated by CORSIKA, bottom panel by GEANT4. Here the notation of the top panel should be read as E_{proton}.

The proton components for incident neutrons are shown in Fig. 5. The GEANT 4 and CORSIKA codes yield nearly identical results. However, for the neutron components, the GEANT 4 prediction is doubles that of CORSIKA (Fig. 4). This stems from the fact that the contribution of anti-neutron production in the early stages of the nuclear cascade was not included. This effect will be evaluated by the time of the conference.

Discussions and Summary

We have calculated the energy spectra of secondary components of cosmic rays that are produced by the collisions of energetic solar particles in the atmosphere at various altitudes. The spectra will be used in future analyses of SEPs. To obtain fluxes of primary solar particles at the top of the atmosphere, the intensity of the secondary cosmic rays observed by neutron monitors or plastic scintillator needs to be divided by the value shown on the vertical axis, after correction of the detection efficiency of each detector. Thus we will be able to deduce the energy spectra of solar particles in a wide range of solar particles from 10 MeV to 1000 GeV. This will enable the shock, stochastic and DC acceleration processes at the solar surface to be differentiated.
In the course of these studies we noted various, minor discrepancies between results obtained using the CORSIKA and GEANT4 codes. These will be investigated in the future.

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