Unsolved problems in EAS observation

The origin of UHECR
Recent extensive air shower (EAS) observations have brought the precise energy spectra of ultra high energy cosmic ray (UHECR), and their results clearly have shown falling-off of the cosmic ray flux above 1020 eV[1]. There are thesis as for the mechanism of this rapid dropping, but no established one. One of the big reason of the difficulty of the interpretation of the energy spectrum comes from the uncertainty in the determination of primary UHECR composition.

Energy scale difference between FD and SD
Telescope Array group compared the primary cosmic ray energy calculated using fluorescence detector telescopes (FD) data and one using surface particle detector array (SD) data, and found that SD energy scale is about ±27% higher than the FD. Recent TA's studies suggested the shrinking of the lateral distribution of secondary particles on the ground. A study of the radial variation of shower front structure above 1031 eV which was evaluated using "local age parameter" showed a consistency with the iron-induced air shower, although TA composition measurement result agreed more closely with the proton than the iron[2]. Another study was the lateral distribution of the SD signal size in the primary energy range 1018 – 1032 eV. The discrepancy between measured SD signal size and MC prediction value was increased along with the distance from the shower core[3]. Excessive secondary particle far from shower core in TA data may be an indication of the excess of muons in EAS.

Muon excess on the ground
Water-Cherenkov type SD of Pierre Auger Observatory could count the number of muons in EAS, and was observed the surplus muon on the ground[4]. While the numbers of electromagnetic component agreed with the predicted of the hadron interaction model, 3% more muons were detected than predicted by the QGSJET-II1[5] and 60% more were detected than predicted by the QGSJET-II04[6].

Information from accelerator experiment

Forward neutron spectrum

Fig.1 Forward neutron energy spectra for 7 TeV pp collision

LHCf neutron spectra[7] compared with LHC-tuned model predictions. In the most forward pseudo-rapidity (η) range, QGSJET-II04 model predicts higher neutron production rate than the experimental result. However, the prediction of QGSJET-II04 model is clearly smaller than the measured neutron production rate in the smaller η range. The predicted neutron production rates of EPOS-LHC model are smaller than the LHCf results in all three η ranges.

Forward neutron & n0 energy flow

Fig.2 Forward neutral particle energy flow for 7 TeV pp collisions

The total energy carried by forward neutrons as a function of pseudo-rapidity is shown in the left panel of Fig.2. Curves show the predictions of hadron interaction models which take the energy threshold of LHCf neutron result (E = 500 GeV). Predictions of QGSJET-II04 is relatively similar to data, but is still small around the peak of energy flow distribution. The right panel of Fig.2 shows the n0 energy flux as a function of rapidity in √s = 7 TeV pp collisions calculated using published data[8]. For the n0, all models are consistent with data above y = 2.

Model modification

Increase the forward baryon
To increase baryon energy flow at very forward region in QGSJET-II04, I make a trial of increasing the events whose leading particle are As. The developed method is as follows.
1. Select events whose leading particles are nucleon.
2. A part of these events are converted to events whose leading particles are As.
To obtain the probability of event conversion (Pconv) using the LHCf neutron energy spectra, a standard x2 method is adopted. The definition of x2 is as follows.

The minimum of x2 is at Pconv = 0.445.

Neutron energy spectra and energy flux of modified model are shown in Fig.1 and Fig.2 respectively. Data/MC differences in energy spectra and energy flow distribution are improved.
The n0 energy flux of the modified model is shown in the right panel of Fig.2. At the very forward region, difference between original QGSJET-II04 and the modified model is not very large.

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Impact on air shower development

Summary of EAS simulation results
The impact of the modification of forward baryon energy spectrum is as shown in Fig.4 & 5.

Modified model predicts the smaller shower maximum position than original one. With this modified model, forward neutron spectrum becomes more softer than the predictions of current hadron interaction models. Then inelasticity becomes larger so that air shower develops more quickly than the simulation with original interaction model.

Fig.3 Multiplicity and Inelasticity in proton-Air collision

Fig.4 Longitudinal development of proton-induced air shower

Fig.5 Total # of muons at TA altitude

The total number of muons on the ground is increased. The baryons generated to the forward region is related to the number of muons observed on the ground. Unlike n0s which decay immediately into two photons and give the energy to the electromagnetic cascade, baryons can still interact and produce charged pions which then decay into muons.