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A possible approach to check the interaction models by observing AS cores around 20 TeV at 4300 m a.s.l.

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A Monte Carlo study shows that, using an air shower core detector set up at 4300 m a.s.l., we can observe the high energy electromagnetic component in an air shower core induced by a primary particle of around 20 TeV region, where the primary composition is well known. It provides direct check of the hadronic interaction models currently used in the air shower simulations, for example QGSJET, SIBYLL etc. In present paper, the method of the observation and the sensitivity of the characteristics of the observed events to the different interaction models are discussed.

1. Introduction

The study of high energy cosmic rays has to rely on the indirect observation of air showers (AS) produced by primary particles. To interpret the AS data, Monte Carlo (MC) simulation is inevitable. The hadronic interaction models used in any Monte Carlo codes were built based on some theoretical scenario that was checked by accelerator experiments up to the hadron collider energies and extrapolated to the higher energies. It is noted that discrepant results on the studies of the cosmic ray composition at the knee energy region were reported by several recent cosmic ray experiments. The Kascade experiment [1] uses the unfolding method to resolve the elementary mass groups based on the correlation between the number of electrons and muons which is a parameter sensitive to the primary mass. The Tibet experiment [2, 3] observes air shower core with calorimetric detectors with which the air showers induced by light elements are more efficiently triggered than those by heavy elements. If using SIBYLL interaction model in the analysis, the results both from Kascade and Tibet experiments are almost consistent, and show the dominance of heavy elements at the knee energy region. However, a large disagreement arises when one uses QGSJET model, where the Kascade experiment shows strong dominance of the light elements [1], while the Tibet experiment still shows dominance of heavy elements at the knee energy region. Nonetheless, the absolute proton fluxes observed by the Tibet experiment using SIBYLL and QGSJET model have about 30% difference. Such situation is partly due to the differences in the modeling including how the extrapolations are made up to cosmic ray energies, and partly due to the experimental systematics. Therefore, it is still a topic of debate how much of the discrepancy comes from the experimental systematic errors and how much, from uncertainties in the modeling used to describe the shower development. Thus, more checking and improvements on the hadronic interaction models are necessary. For the development of the air showers, the most forward region of the produced secondaries in the hadronic interactions are important, where, although it contains very few particles, a large fraction (say, more than 90%) of the collision energy is carried. This region can be studied by observing the high energy electromagnetic component at the air shower core. Here we propose an approach to carry out experimental test on currently used interaction models by observing AS cores at an energy region where the primary composition is better known, using the new type of AS core detector YAC (Yangbajing Air shower Core detector) that is planed to be set up at Yangbajing, 4300 m a.s.l. in Tibet [4, 5].

2. Method

The primary composition at the energy region around 20 TeV has been better measured [6, 7]. We may directly use it as input to avoid the interruption induced by the uncertain primary composition, as in the case at the knee energy region. We take the same design of the AS core detector YAC, which is originally designed for the observation of the heavy component at the knee. It consists of 400 burst detectors of 0.20 m^2 placed in a grid with 3.75 m interval to detect the high energy electromagnetic component. Each burst detector consists of lead plates of the total thickness 3.5 cm above the scintillator attached with the photomultipliers. The only difference is in the spacing. For the current purpose all detector units should be placed as densely as possible (YAC−low energy mode). But for realistic reason some non-zero spacing is necessary. In the following a 50 cm spacing between two neighboring detectors is taken.

3. Simulation and Analysis

A Monte Carlo simulation has been carried out on the development of AS in the atmosphere and the response in the burst detector. The simulation code CORSIKA (version 6.200) including QGSJET01c and SIBYLL2.1 hadronic interaction models [8] are used to generate AS events. Primary composition is taken from JACEE and RUNJOB experiments [6, 7]. The incident zenith angles of primary particles are isotropically sampled within 60 degrees. The minimum primary energies are set to 2 TeV. For each simulated AS event that reaches the observation level, its core is dropped randomly onto an area of 49.5 m × 47.5 m, which includes the marginal space of 15 m outside the detectors. The electromagnetic showers in the lead layer are calculated based on the detector simulation code EPICS [9]. The number of shower particles hitting a detector unit is called 'burst size' N_b. When the burst size of a detector unit is higher than 100, this unit is defined as a 'fired' one. We also call the total burst size of all fired detector units as $\sum N_b$, the maximum burst size among fired detectors as N_b^{top}.

The selection criteria of the events are set so that the responsible primary energies are mostly around 20 TeV, which leads to (1) the number of fired detectors $1 \leq N_d \leq 8$, (2) the sum of the burst size $1500 \leq \sum N_b \leq 10000$, (3) the detector unit with N_b^{top} is located at inner area of BD grid excluding the most outer edges. The last condition is used to reject the detection of the outskirts of the events falling far from the array. We sampled 1.75 $\times 10^8$ and 1.71 $\times 10^8$ primaries for the QGSJET and SIBYLL model, respectively. Then we obtained 24187 and 32290 burst events for the QGSJET and SIBYLL models, respectively. The average generation efficiencies of the burst events in this energy by SIBYLL is higher than QGSJET by a factor 1.37. The fractions of the components after the burst event selection are summarized in Table 1.

It is worthwhile to note that ∼90% of the selected burst events are induced by protons and helium nuclei. This is suitable for our aims because primary proton and helium spectra have been better measured than other heavier nuclei [6, 7], and the systematic uncertainty induced by other nuclei will be smaller than 10%. In order to investigate the performance of the detector and the possibility of the observing interaction model dependences, the MC data were analyzed in the same manner as in the procedure for the expermental data analysis.

Table 1. The fractions of the components after the burst event selection.

Int.model		Primary Energy (TeV)	P	He	M	H	VH	Fe
QGSJET	After burst-event selection (%)	2 - 20	92.6	7.2	0.20	0	0	0
		20 - 200	64.5	25.8	5.2	2.5	0.5	1.6
SIBYLL	After burst-event selection (%)	2 - 20	90.5	9.2	0.30	0.04	0	0
		20 - 200	61.3	27.0	5.9	2.9	0.7	2.2

4. Results and Discussion

The spectrum of the total burst size $\sum N_b$ and the top burst size N_b^{top} are obtained as shown in Fig. 1 and Fig. 2, respectively. The differences of the flux intensity between two interaction models are 1.40±0.01 in Fig. 1 and it is a little more pronounced in Fig. 2 being 1.45±0.01 reflecting the features of the models in the most forward region. The first check point of the YAC observation is the comparison of the burst size flux with these MC predictions, which is dependent on the modeling of the production spectrum in the very forward region as well as the inelastic interaction cross section.

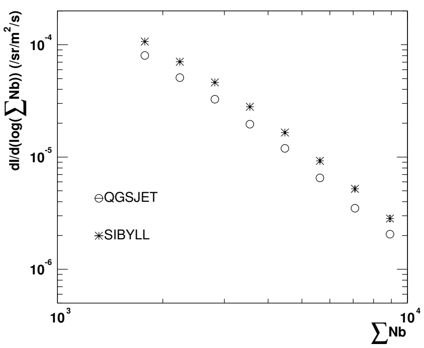

Figure 1. The total burst size ($\sum N_b$) spectrum obtained by QGSJET and SIBYLL model.

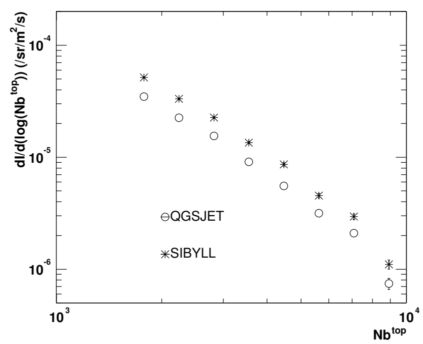

Figure 2. Top burst size (N_b^{top}) spectrum obtained by QGSJET and SIBYLL model.

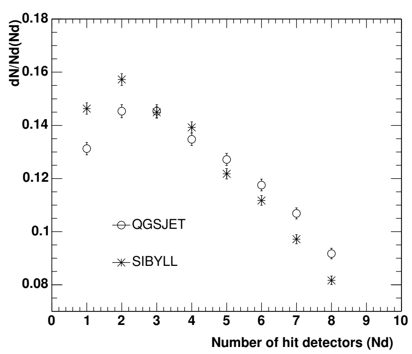

Figure 3. The spectrum of the number of hit detectors (N_d) obtained by QGSJET and SIBYLL model.

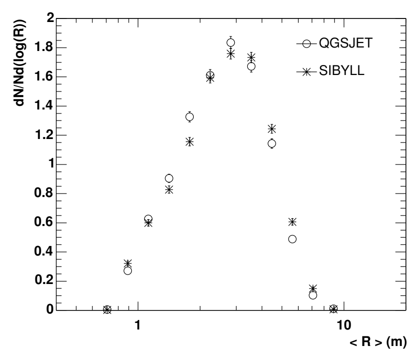

Figure 4. Distributions of the mean lateral spread ($< R >$) obtained by QGSJET and SIBYLL model, by requiring $N_d \geq 5$.

The uncertainties involved in the absolute primary fluxes obtained by the direct observations may cause some difficulties in concluding the validity of the given model at present, however, precise measurement of the primaries are also expected in near future, for example by ATIC [10] and CALET [11]. The second interest is to investigate the lateral characteristics of the air shower core. The number of fired detectors N_d reflects the lateral characteristics of the burst events. The N_d distributions are shown in Fig.3, in which one can notice a visible model dependence between QGSJET and SIBYLL. Fig. 4 shows the mean lateral spread ($< R >= \sum r_i/N_d$) of each burst events by requiring $N_d \geq 5$, where r_i and N_d are the lateral distance from the air shower core to a fired detector unit, and the number of hit detectors, respectively. Although the difference is small in this statistics, the tendency of the wider lateral spread in SIBYLL model than in QGSJET can be seen. Such differences as seen in lateral features are free from the uncertainties of the primary absolute intensity and provide a check on the modeling in the very forward region. The expected number of events per one year is estimated as $\sim 1.8 \times 10^6$ events, by which some of the models can be ruled out.

Putting the above together, the experimental test on the hadronic interaction models used in the AS simulation codes can be made at primary energy around 20 TeV by YAC−low energy mode with high statistics.

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