The Telescope Array Experiment: Hybrid Measurement of Ultra High Energy Cosmic Rays in Northern Hemisphere

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Abstract

The result of AGASA shows the extension of the cosmic ray energy spectrum above the GZK cut-off. Several new generation experiments are planned or under construction to identify the origin of such ultra high energy (UHE) cosmic rays exceeding the cut-off. We report here the design of hybrid Telescope Array (TA) and introduce plans of improving the accuracy of measuring the energy spectrum by the hybrid measurement of ground array and air fluorescence telescope.

1. Introduction

The AGASA energy spectrum shows that there is no indication of GZK cut-off expected by the photo-pion production of the ultra high energy cosmic rays. There is also an indication of point sources in the arrival direction of such cosmic rays [1]. If the origin of these cosmic rays is some type of already known astronomical object, it must exist within several tens of Mpc from our galaxy. Until now no astronomical object is identified in the directions of the observed UHE cosmic rays. Several top-down models are proposed as a remedy, in which UHE cosmic rays are produced via anomalous physics processes or by unknown astronomical objects [2]. In order to get a definite answer on the origin of UHE cosmic rays, it is crucially important to measure the energy spectrum, the arrival distribution and the composition more accurately and compare them with the predictions of these models. We therefore proposed the Telescope Array as the next generation air shower experiment [3] and planned to observe air showers by the air fluorescence technique. On the other hand, HiRes group recently reported that there is a GZK cut-off in their observed energy spectrum [4]. It seems clear

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that a part of the inconsistency is due to the systematic error of both experiments in the determination of primary cosmic ray energies [4]. Taking this critical situation into account, we now intend to observe air showers with an AGASA type ground array and with an air fluorescence detector simultaneously as the first step of the TA project. In this paper, we present a simulation study to confirm how much the systematic error is improved in the primary energy estimation by using our hybrid detector.

2. Experimental Plan

Fig. 1. The prototype camera and telescope reflector for the fluorescence measurement.

In our design of the hybrid-TA, an array of 24×24 plastic scintillators covering the ground area of 760 km^2 is surrounded by three air fluorescence stations. The West Desert in Utah, USA is taken as the experimental site. The total field of view of each station is $3^\circ - 34^\circ$ in the elevation angle and 120° in the azimuthal angle, with all of the three stations looking toward the center of the ground array. The separation of the station is $30 - 40$ km and the stereo acceptance is $\sim$670 km^2 sr for UHE cosmic rays falling within 45 km of the station. The fluorescence acceptance alone is 4 times larger than that of AGASA assuming 10% duty factor. Approximately 60% of the events for E $> 10^{20}$ eV is observed by all 3 stations.

The field of view of each telescope is 18.0° in azimuth and 15.5° in elevation. The telescope has a spherical dish of 3.3 m diameter composed of 18 hexagonal segment mirrors (see Fig.1). The focal length is 2960 mm and the spot size on the focal plane is $\sim$30 mm in FWHM according to a ray tracing calculation. The air shower image is recorded by a camera composed of 16×16 2-inch PMTs placed on the imaging plane (see Fig.1). Each PMT pixel covers $1.1^\circ\times1.0^\circ$ patch of the sky. A signal from the PMT is amplified by a factor of 4 with a pre-amplifier and is sent to a Charge Successive Integrators (CSI) circuit. The CSI integrates a signal every 200 ns and send it out successively to a 12-bit pipeline ADC by means of 3 capacitances operated in a rotational sequence. A self-ranging H/L gain scheme is adopted to cover a dynamic range corresponding to $1-64$k photoelectrons. The digitized signal is fed to a Digital Signal Processor (DSP) to search for a fluorescence signal by maximizing the S/N ratio in 25.6 μs time window.

By one year operation of the hybrid-TA, we will collect $\sim$12 events with E $> 10^{20}$ eV and more than 900 events with E $> 10^{19}$ eV, of which $\sim$80 events are measured simultaneously by both the scintillation detector array and the air fluorescence telescopes.

3. Simulation Procedure

The simulation of UHE cosmic rays by the full Monte-Carlo is practically prohibited by the computation time. In our analysis of the hybrid event, we first generate UHE events using a thinning method. The proton is assumed as a primary and the first interaction depths are sampled by the Monte Carlo simulation. The longitudinal development (LD) profiles are calculated analytically with a modified Gaisser-Hillas function, in which 6 parameters characterizing LDs are estimated with empirical formulas. These formulas are derived from the results of a small amount of simulated events with Corsika Monte Carlo package. Fluorescence and Cherenkov photons are generated according to the LD function and the transmission of photons in the atmosphere is simulated taking effects of Rayleigh and Mie scattering into account. For the determination of the primary energy, it is important to estimate the effects of these scatterings accurately. Note that in the event generation we adopted 1.2 km for the aerosol scale height, h, and 20 km for the attenuation length for the Mie scattering. In the final stage of the simulation, PMT output signals are generated by taking optical properties of the telescopes and cameras into account. The produced shower signal was analyzed, and its energy and arrival direction were reconstructed by the χ^2 minimization method. Details of the analysis procedure are described in our design report [3].

4. Method to Improve Systematic Error

Following is one of the ways we are considering to improve the systematic error of the energy determination using the hybrid event. (a) First a primary energy, E, and an air shower size at the array altitude, N_F, are estimated with a corresponding LD profile reconstructed by the air fluorescence measurement. (b) Then the obtained E is corrected by multiplying a factor N_G/N_F, where N_G is the measured shower size by the ground array. In the AGASA experiment, the primary energy is estimated from the observed local particle density at the core distance of 600m. In this procedure, a major part of 18% total systematic error comes from the uncertainty in the adopted Monte Carlo simulation notably from the differences of used hadronic interaction models and the assumed primary composition. On the other hand, the measurement of N_G itself can be as good as 10% or better, and this is used for the correction of E in our method. In the following analysis, we artificially produced ~20% systematic error in the fluorescence energy measurement by reconstructing the LD profile using a“wrong scale height of 2.0 km and 0.4 km against 1.2 km used in the event generation. Whereas the value of N_G at the array altitude is generated by smearing the correct shower size by 10%.

5. Result

The simulation is performed for primary energies of 10^{19}, 10^{20} and 10^{21} eV with zenith angles less than 60° and with impact parameters from the center of the ground array less than 10 km. For each primary energy, 200 events are generated. The result for the events with E = 10^{20} eV is shown in Figure 2. Before the correction, the estimated energies are ~14% less or ~21% more than the generated value of 10^{20} eV by adopting the wrong scale height of 0.4 km or 2 km. This is shown in the upper panels of Figure 2. After the correction, the systematic shift of the measured energy is reduced as seen in the lower two panels of the Figure 2. The present results are summarized in Table 1. It is shown that even when there is ~20% systematic shift in the air fluorescence energy measurement, we can reduce the error within ~10% by adopting our method with a minor sacrifice in the resolution. Now we are improving our reconstruction program in order to reduce the systematic error even further.

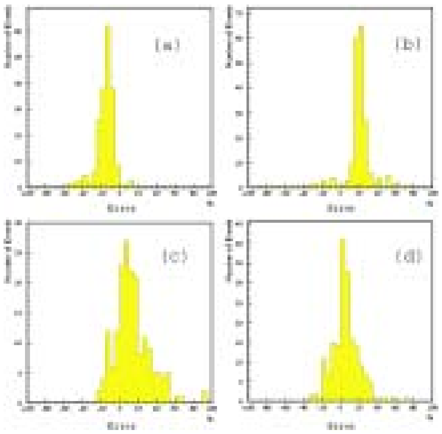

Fig. 2. Distributions of the energy measurement errors for E = 10^{20} eV by using a "wrong scale height of 0.4 km (a and c) and 2 km (b and d).

Table 1. The improvement of the systematic error.

E (eV)	Adopted h (km)	av. E shift ± resol. before correction	av. E shift ± resol. after correction
10^{19}	0.4	$-9.5 \pm 6.0\%$	$+14.9 \pm 16.7\%$
10^{20}	0.4	$-13.9 \pm 6.3\%$	$+10.1 \pm 18.4\%$
10^{21}	0.4	$-17.7 \pm 6.8\%$	$+8.6 \pm 17.1\%$
10^{19}	2.0	$+21.7 \pm 6.0\%$	$-4.1 \pm 12.5\%$
10^{20}	2.0	$+21.2 \pm 4.8\%$	$+4.8 \pm 13.1\%$
10^{21}	2.0	$+21.8 \pm 5.8\%$	$+2.9 \pm 11.7\%$

References

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