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Chemical composition of ultra-high energy cosmic rays estimated by muon measurement with AGASA

K. Shinozaki[b], M. Chikawa[c], M. Fukushima[a], N. Hayashida[a], K. Honda[d], N. Inoue[e], K. Kadota[f], F. Kakimoto[g], K. Kamata[h,1], S. Kawaguchi[i], S. Kawakami[j], Y. Kawasaki[k], N. Kawasumi[l], K. Mase[m], S. Mizobuchi[n,b], M. Nagano[o], H. Ohoka[a], S. Osone[p], N. Sakaki[q], N. Sakurai[m], M. Sasano[r], H.M. Shimizu[k], M. Takeda[a], M. Teshima[b], R. Torii[a], I. Tsushima[l], Y. Uchihori[s], T. Yamamoto[t], S. Yoshida[m] and H. Yoshii[n]

(a) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan
(b) Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany
(c) Department of Physics, Kinki University, Osaka 577-8502, Japan
(d) Faculty of Engineering, Yamanashi University, Kofu 400-8511, Japan
(e) Department of Physics, Saitama University, Saitama 338-8570, Japan
(f) Faculty of Engineering, Musashi Institute of Technology, Tokyo 158-8557, Japan
(g) Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan
(h) Nishina Memorial Foundation, Komagome, Tokyo 113-0021, Japan
(i) Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan
(j) Department of Physics, Osaka City University, Osaka 558-8585, Japan
(k) RIKEN (The Institute for Physical and Chemical Research), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
(l) Faculty of Education, Yamanashi University, Kofu 400-8510, Japan
(m) Department of Physics, Chiba University, Chiba 263-8522, Japan
(n) Department of Physics, Ehime University, Matsuyama 790-8577, Japan
(o) Department of Space Communication Engineering, Fukui University of Technology, Fukui 910-8505, Japan
(p) National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8561, Japan
(q) Department of Physics and Mathematics, Aoyama Gakuin University, Sagamihara 229-8558, Japan
(r) Environment and Energy Department, National Maritime Research Institute, Tokyo 181-0004, Japan
(s) National Institute of Radiological Sciences, Chiba 263-8555, Japan
(t) Center for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
Presenter: K Shinozaki (kenjikry@mppmu.mpg.de), ger-shinozaki-K-abs3-he14-oral

The chemical composition of ultra-high energy cosmic rays (UHECRs; $> 10^{19}$ eV) is a key parameter to understand their nature and origin. In the Akeno Giant Air Shower Array (AGASA) experiment, we measured the muon density at 1000 m from the cores for 159 UHECR events. The data were interpreted by the recent CORSIKA simulation (version 6.203) with QGSJET01 and SIBYLL2.1 interaction models. The data is consistent with light components for the QGSJET model. No positive signature has been found for the gamma ray dominance. In the presentation at the conference we will report detailed results and comparisons with the results from other experiments.

1. Introduction

The origin and nature of the ultra-high energy cosmic rays (UHECRs; referring to as above 10^{19} eV) are still unsolved mysteries in contemporary astrophysics [1]. To answer this question, the arrival direction distribution and the chemical composition would be key parameters for air shower experiments. Because of their globally isotropic arrivals in the observed sky, UHECRs are considered to originate in extragalactic space. Concerning small-scale anisotropy, clusters have been found among observed events [2], while any individual objects such as AGNs and hot-spots of radio galaxies supported by '*bottom-up*' models [3] have not been identified as an evident UHECR source. The chemical composition has been investigated including even lower energies by characterising the shower development or muon content on the ground [4]. Its importance is more pronounced in '*top-down*' models as an alternative scenario [5]. These models expect the presecen of UHE gamma ray component from the decay or interaction of super-massive particles or super-high energy relic neutrinos, while no nucleus is produced in these processes.

In the present work, we studied the chemical composition of UHECRs by the measuring the muon component in the Akeno Giant Air Shower Array (AGASA) experiment [6]. For the comparison with the simulation results, we generated a number of showers using the CORSIKA code (version 6.203) [7]. Due to uncertainties in high energy hadronic interactions, we tested two different models for $E_{\rm lab} > 80$ GeV____QGSJET01 [8] and SIBYLL2.1 [9]. For low energy hadronic interactions, we used the FLUKA code [10]. For gamma ray showers we used the QGSJET model with the PRESHOWER option [11] in CORSIKA applied for interactions in the geomagnetic field above the atmosphere [12]. On the response of surface detectors, we investigated in [13] using the GEANT programme [14]. We also took into account the configuration of the array, the response of muon detectors and the analysis procedure as described below.

In the following we report the result of the muon data analysis from the AGASA experiment. A preliminary interpretation is also presented mainly with the QGSJET model. The CORSIKA code is widely used by various groups and it would therefore be useful for comparison with results from other experiment. It should be noted that our previous data interpretation [15] was based on the AIRES code [16] with the QGSJET98 model and the geomagnetic effect simulation by [17]).

2. Experiment

The AGASA experiment was operated deploying 111 surface detectors over an $\sim$ 100-km^2 area. The site is located $\sim$ 100 km west of Tokyo at an average altitude of 667 m (957 g/cm^2 in atmospheric depth). In the southern region of the array, we also built 27 muon detectors (2.8–10 m^2) that consisted of 14–20 proportional counters aligned below an absorber (30 cm iron or 1m concrete; threshold muon energy of 0.5 GeV for vertical incidence) [18]. With surface detector data, we estimated the primary energy, E_0, for each observed shower by a local charged particle density at 600 m from the core, $S(600)$ [19]. The determination error of E_0 was evaluated to be $\pm 30\%$ at $10^{19.5}$ eV and $\pm 25\%$ at 10^{20} eV [20]. The energy scale is based on $S(600)$ for hadronic showers, hereafter. The chemical composition study has been carried out through the measurement of muons for a part of observed events. Due to sparse detector distribution and a relatively narrow dynamic range for muon density measurements, we employed the muon density at 1000 m from the core, $\rho_\mu(1000)$, as a primary mass estimator. For each event, $\rho_\mu(1000)$ [m^{-2}] was determined by fitting the data in 800–1600 m from the shower core with the empirical lateral distribution formula [21]. The determination error of $\rho_\mu(1000)$ is evaluated to be $\sim 40\%$ for hadronic showers above 10^{19} eV [15]. Here, we selected showers incoming from zenith angles $\leq 36^\circ$ with two or more available muon density measurements. Requiring these criteria against the database between December 1995 and January 2004, the muon measurements of 159 (21) showers above 10^{19} eV (above $10^{19.5}$ eV) were parameterised by $\rho_\mu(1000)/E_0$ where E_0 is in a unit of 10^{19} eV.

3. Results and discussion

Figure 1 shows the average of $\rho_\mu(1000)/E_0$ as a function of E_0. The data are plotted by closed circles with error bars. The averages expected for different primaries are drawn by curves as labelled. Solid and dashed curves correspond to QGSJET and SIBYLL models. For this particular comparison, the primary spectrum for simulations was assumed to be $\propto E^{-3}$ in differential form.

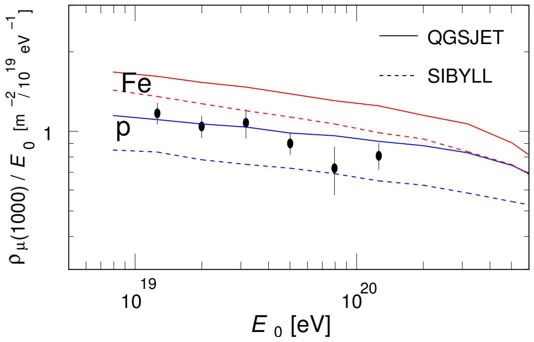

Figure 1. $\langle\rho_\mu(1000)/E_0\rangle$ as function of E_0. The averages expected for proton and iron are shown by curves as labelled. Solid and dashed curves correspond to QGSJET and SIBYLL models, respectively.

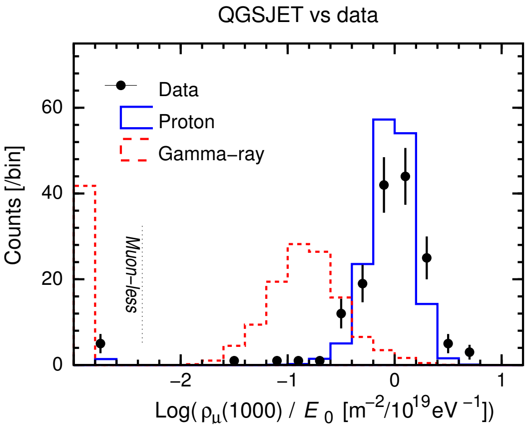

Figure 2. Distribution of $\rho_\mu(1000)/E_0$ for events above 10^{19} eV. For comparison, simulated distributions with the QGSJET model are drawn for proton (solid line) and gamma ray (dashed line).

The relationship between $\langle\rho_\mu(1000)/E_0\rangle$ and E_0 indicates for either model assumed that the data is consistent with a composition among hadron components. With the QGSJET model, the chemical composition is favoured with the light component. If one assumes the SIBYLL model, the estimated composition would be relatively heavy. Between two models, the difference in $\rho_\mu(1000)$ for proton is 33% at 10^{19} eV. Such a model dependence is reflected in behaviour of air shower developments as simulations with SIBYLL show the depth of the shower maximum $X_{\max}$ deeper than those with QGSJET [22]. However, such discrepancies in expected observable values have become less deviating among newly modified models. For example, the corresponding difference of muon density was nearly 60% between QGSJET98 and SIBYLL1.6 models [23].

Figure 2 shows the distribution of $\rho_\mu(1000)/E_0$ for events observed above 10^{19} eV. The data are plotted by closed circles with statistical error bars. For comparison, the simulated distributions with QGSJET are drawn for proton (thick lines) and gamma ray (dashed lines). The primary flux of each component is separately normalised to fit the number of observed events in each energy bin with a $\Delta \log E_o$ = 0.2 width.

From this figure, the data does not show a strong signature expecting the gamma ray dominance. To follow the manner used in [15], we estimated an upper limit on the faction of gamma ray initiated showers among all events by assuming proton plus gamma ray primaries. Under the current simulation study, with the QGSJET model, the limit at a 95% confidence level is yielded to be 43% above $10^{19.5}$ eV. At the highest energies, a certain possibility remains for gamma ray primaries. With the SIBYLL model, the limit on the gamma ray fraction is even smaller, while in this case the proton dominance is also unlikely.

For this estimation, there are possible sources of systematic uncertainty which would affect upper limits at lower energies. Compared with the previously reported result apart from an increase of statistics by $\sim$ 20%, there are some comparable differences in outputs of the simulation. For example, each $\rho_\mu(1000)$ distribution has more compact spread and separates from the counterpart at any energy of interest. This difference might come from either/both air shower simulations or/and geomagnetic effect simulations. The former includes the modelling of the Landau-Pomeranchuk-Migdal effect [24] and that of photonuclear interaction. To better understand such uncertainties, a further investigation is in progress.

To summarise, we analysed the data of muons in UHECR air showers in the Akeno Giant Air Shower Array (AGASA) experiment. The data were interpreted using the recent CORSIKA. With the QGSJET01 model, the data is favoured with light components. No positive signature has been found for the gamma ray dominance. At the highest energies, the composition of UHECR is unclear. To find the clues, the reanalysis and comparison with simulations are being prepared. In the conference we will report those studies in more detail as well as comparisons with results from other experiments.

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