Cosmic-ray energy spectrum around the knee

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Interesting global and fine structures of cosmic-ray energy spectrum have been reported by recent direct observations and air-shower experiments. Possibilities of interpreting these structures in terms of nearby sources or an acceleration mechanism of cosmic rays are presented focusing on the chemical composition measurement by CREAM, Tibet and KASCADE experiments. Interaction model dependence involved in the air-shower analysis is also discussed referring to the LHC$_f$ data.

1 Introduction

Direct measurement of cosmic-ray energy spectrum has been recently extended up to 10^{14} eV region by long duration balloon flight of ATIC [1], CREAM [2] and TRACER [3] with much higher statistics than earlier works. In the higher energy range, ground based experiments using air-shower arrays also obtained all-particle spectrum with high statistics in the energy range $10^{14}-10^{17}$ eV covering the knee. Although the primary mass resolution in air-shower experiments is limited, the energy spectra for given mass groups are obtained in these experiments too. Tibet [4] experiment obtained proton and helium spectra using a shower core detector which captures the high energy particles around the shower axis. Such information well reflect the first interaction point of the shower development and they are used for separating air showers of light-nuclei origin. Because of the long interaction mean free path in the atmosphere, light primaries such as protons and helium are preferably selected by adopting high energy threshold for the core detector (energy flow of the order of TeV per m^2). Artificial Neural Network is applied to remove the contamination of air-showers of heavier nuclei origin. KASCADE [5] and GRAPES [6] used traditional method for investigating chemical composition using $N_e - N_\mu$ correlation, where N_e is the number of electrons and N_μ the number of muons at the observation level. The energy spectra of five mass groups were reported by them for proton, helium, CNO, Si and Fe from the analysis using unfolding method on the shower size spectrum. H.E.S.S. [7] experiment also reported iron spectrum, with higher statistics than any direct observations, by observing direct Cherenkov light using imaging Cherenkov telescope.

The energy spectrum of cosmic rays has been thought to follow simple power law except the change of the power index at the knee, however, the compilation of these new data revealed interesting global and fine structures, which are characterized by a sharp knee of all-particle spectrum at 4 PeV seen in air-shower data and a hardening of the spectra of primary nuclei at 200 GeV/nucleon seen in direct observations. An enhancement of electron spectrum is also reported at several hundred GeV range [9,10,11], which is discussed in a context of a nearby source scenario, cosmic-ray acceleration mechanism or particle physics scenario.

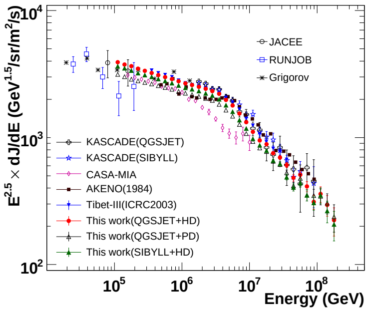

Figure 1: Compilation of all-particle spectrum around the knee.

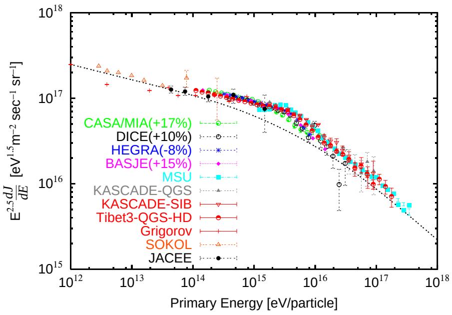

Figure 2: Normalized all-particle spectrum by energy scale correction as indicated in a parenthesis (only four experiments are corrected). Dashed line expresses the extrapolation of direct measurements using broken power law (see the text).

In this report, possible models of the origin of the knee are discussed. The interaction model dependences involved in the air-shower analysis are also discussed in comparison with LHC$_f$ data [8].

2 All-particle spectrum

Compilation of cosmic-ray all-particle spectrum around the knee is shown in Fig.1 using limited number of works to avoid too complicated plots, where perpendicular axis is multiplied by $E^{2.5}$ to make clear the change of power index of the spectrum. Although the disagreement among various works is not sufficiently small, the spectral shapes are similar each other. The cause of such disagreement can be attributed to the systematic error in the energy scale involved in each experiment. As shown in Fig.2, many works agree well when a normalization is made by applying the energy scale correction appropriately as indicated in the parenthesis of the data label in the figure. Global feature of the spectrum around the knee can be expressed, as shown by a dashed line in Fig.2, by summing up spectra of each elements extrapolated from direct measurment using a broken power law,

$$\frac{dj}{dE} = j_0 E^{-\gamma}(1 + E/\varepsilon_b)^{-\Delta\gamma}, \tag{1}$$

where ε_b expresses the break point of the spectrum of each element with rigidity dependent assumption, i.e., $\varepsilon_b = z \times \varepsilon_p$, where ε_p is the break point of proton spectrum, z is the atomic number, and γ is the power index before the break point, $\Delta\gamma$ is the increase of the absolute value of the power index after the break point. The normalized all-particle spectra after the energy scale correction are in good agreement each other showing a sharp knee at 4×10^{15} eV and a remarkable enhancement of the spectrum over the extrapolation of the direct measurement can be seen. Such a sharp change of the power index cannot be expected from the point of view of the diffusion of cosmic rays in our galaxy.

3 Chemical composition of cosmic rays

3.1 Direct observations

Investigation of the chemical composition of cosmic rays is basically important to understand the knee. At the energies below 10^{12} eV, protons are the major component and helium has

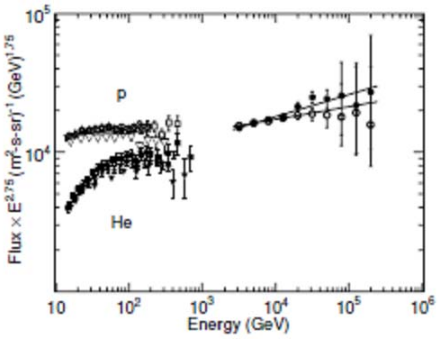

Figure 3: Proton and helium spectra measured by CREAM showing hardening in TeV range and harder helium's power index than protons.

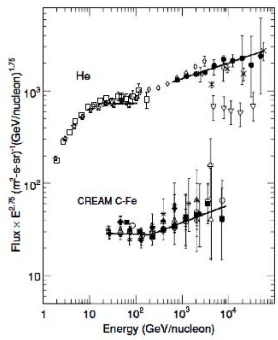

Figure 4: Similarity of hardening at 200 GeV/nucleon for all nuclei shown by CREAM data.

the second contribution, while heavier nuclei are the minority. However, direct measurements over 10^{12} eV recently carried out by ATIC and CREAM of balloon flight at south pole reported the hardening of the energy spectrum of each element and also that the power index of nuclei becomes harder than protons as shown in Fig.3 and Fig.4 that means their contribution to the all-particle spectrum becomes more important toward the knee.

3.2 Air shower experiments

The chemical composition at higher energy range covering the knee is investigated by ground based air-shower experiments. Proton and helium spectra obtained by Tibet and KASCADE are shown in Fig.5 and Fig.6 for two results using interaction models of QGSJET and SIBYLL, respectively. Since the primary energies and particle species are estimated based on shower simulations in which high energy hadronic interaction models are assumed, the interaction model dependence cannot be excluded in the air-shower experiments. The degree of model dependence depends on experimental conditions and methods of analysis. In Tibet experiment, the systematic error due to interaction model dependence is estimated to be within 30% in deriving absolute flux of primaries but there are no serious contradictions in generated event characteristics, for example, as shown in Fig.7 for shower size spectrum and in Fig.8 for burst size spectrum. On the other hand the result of KASCADE experiment shows larger interaction model dependences. One of the causes is the strong model dependence of muon numbers, which plays an important role in KASCADE experiment. The muon size is related to a wide range of multi-particle production spectrum, in other word, the distribution of Feynman parameter x_F, and it is deeply connected with the target effect in nucleus-nuleus (hadron-nucleus) collisions, too. The variation of interaction models in these profiles seems to be still large at present. The

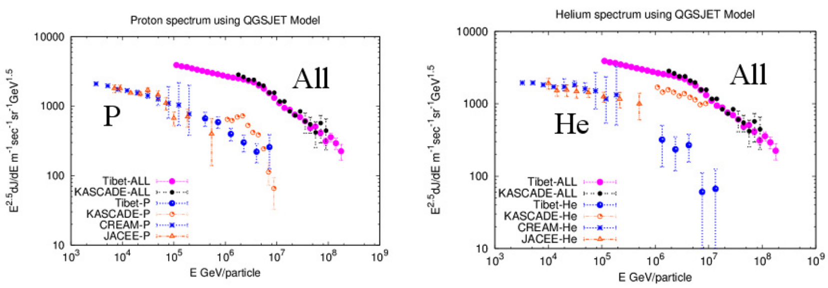

Figure 5: Proton and helium spectra by Tibet and KASCADE using QGSJET model.

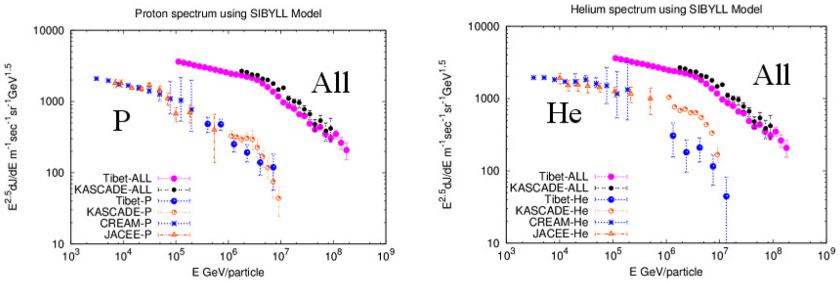

Figure 6: Proton and helium spectra by Tibet and KASCADE using SIBYLL model.

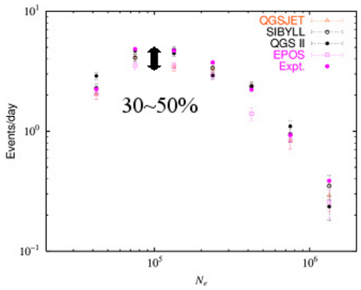

Figure 7: Shower size spectra simulated by four interaction models are compared with Tibet data.

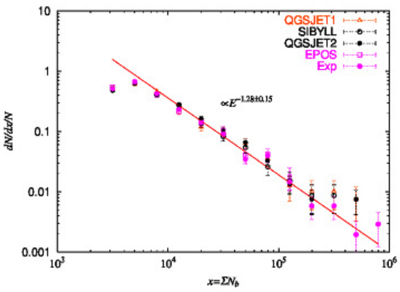

Figure 8: Burst size spectra simulated by four interaction models are compared with Tibet data.

difference of the observation site between Tibet (4300 m above sea level to observe near shower maximum) and KASCADE (near sea level) can be the second reason, because the systematic error of the energy determination and the mass identification can be minimized at the shower maximum.

4 Possible interpretation on the knee

To explain the sharp knee, following two scenarios are considered using CREAM and Tibet data.

4.1 Nearby source scenario

It is assumed that the sharp knee is due to an extra component, presumably due to the contribution of nearby sources, whose chemical composition is dominated by nuclei heavier than helium. Then, the energy spectrum of extra component can be derived by subtracting the diffusive component fitted to CREAM and Tibet data from all-particle spectrum and plotted in Fig.9(a) by closed black circles. Three lines in Fig.9(b) show the energy spectrum of all-particles, proton+helium and nuclei heavier than helium.

4.2 Nonlinear effect in cosmic-ray acceleration mechanism

The nonlinear effect in cosmic-ray acceleration has been studied by many authors [12,13]. Taking into account of the high acceleration efficiency due to the nonlinear effect in diffusive shock acceleration (DSA) process, following source spectrum is assumed.

$$\Phi_s(E,\varepsilon) = j_0 E^{-\gamma_s}[1+\alpha(\frac{E}{\varepsilon})^{\beta}]\exp[-\frac{E}{\varepsilon}], \tag{2}$$

where γ_s denotes the power index of source spectrum, ε the rigidity dependent acceleration limit,

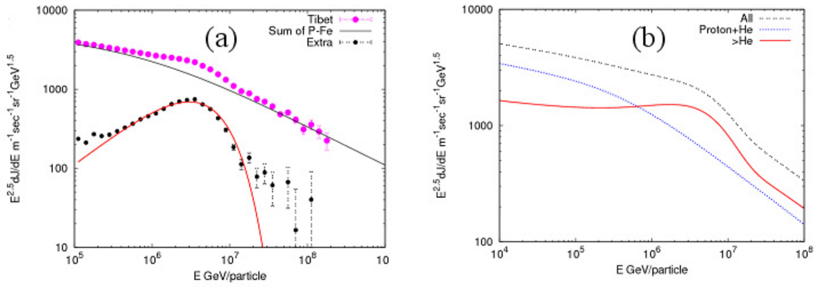

Figure 9: Nearby source scenario : (a) Extra component from nearby source contributes to make sharp knee. (b) Chemical composition of the extra component is heavier than helium leading to heavy dominance around the knee.

α and β are nonlinear-effect parameters to produce a dip and bump in source spectrum as typically shown in Fig.10. The all-particle spectrum is calculated as a superposition of galactic multiple sources [14] with various acceleration limit ε and shown in Fig.11(a). In this model, because of the rigidity dependent acceleration limit the chemical composition becomes heavy dominant toward the knee and beyond as shown in Fig.11(b).

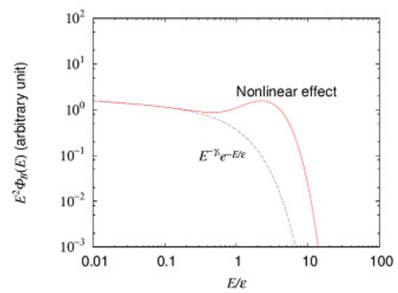

Figure 10: Source spectrum with nonlinear effect in DSA process.

5 LHC$_f$ data and interaction model dependence of air-shower results

Since the development of air showers is dominated by energetic secondaries produced in the atmosphere, the most forward region of the high energy collision is important for air-shower simulation. Many simulation codes are developed taking into account of available high energy data from beam experiments, however, the information of the most forward region was limited in collider experiments and this situation left a room for the ambiguity of the model parameters. LHC$_f$ experiment was carried out to investigate the most forward region and reported first results on single photon production spectrum. The results showed none of the existing models can describe the data well, however, the deviation of the models from experimental data becomes large at limited x_F range where air-shower experiments cannot be affected so much if one takes into account of the cosmic-ray spectrum of the form of the power law. When the x_F-distribution function is written as $f(x_F)$ and cosmic-ray energy spectrum is written by $j(E)dE \propto E^{-\beta-1}dE$,

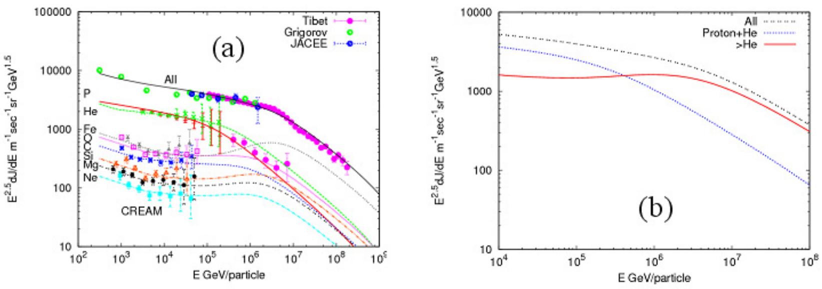

Figure 11: Nonlinear-effect scenario : (a) (b) Chemical composition becomes heavy at the knee and beyond.

effective value of x_F to produce secondary particle of given energy is written as

$$x_{eff} = \int x_F^{\beta+1} f(x_F) dx_F / \int x_F^{\beta} f(x_F) dx_F \qquad (\beta \simeq 2). \tag{3}$$

Numerical calculation using LHC$_f$ data leads to x_{eff} $\simeq$0.37, where the deviation of the models from the data are at most 50% (SIBYLL2.1 PYTHIA8.145), and other models are closer to the data (QGSJETII-03, EPOS1.99). Thus, the ambiguity due to the model dependence in air-shower results are somewhat within 50 % at present, and further tuning of model parameters with LHC data will improve the problem.

6 Summary

Compilation of cosmic-ray energy spectrum in $10^{12} - 10^{16}$ eV range shows interesting global and fine structures. Hard spectrum of nuclei component claimed by CREAM experiment together with low flux of light component (P, He) at the knee claimed by Tibet experiment indicate the knee is dominated by heavy nuclei. Two models of the origin of the knee are discussed in present work. One is to attribute the sharp knee to the contribution of nearby sources whose chemical composition is dominated by heavy nuclei. This scenario can be justified if such nearby sources are detected as high energy γ-ray sources, although no candidates are confirmed yet at present. Another possibility is to confirm the enhancement of the high-energy electron spectrum. High energy electrons cannot travel long distance due to their energy loss proportinal to E^2, therefore some enhancement is expected in their energy spectrm as a result of the contribution of nearby sources (say $<$ 1 kpc) [15]. There are such indications claimed by ATIC [9], Fermi-LAT [10] and PAMELA [11] which reported the enhancement of primary electrons over diffusion model predictions at several hundred GeV. When the extra component at the knee (in PeV region) is iron dominated, it is quite possible that the enhancement of the primary electron spectrum is correlated with the extra component through the hadronic interactions of cosmic rays with interstellar medium at the energy of several tens TeV/nucleon leading to production of hundreds GeV electrons.

The second model is to introduce nonlinear effect in cosmic-ray acceleration mechanism which makes the source spectrum hard around the acceleration limit energy. By this model, a heavy dominant composition is expected at the knee and beyoud. Descrimination of two models can be made by further chemical composition study beyond 10^{16} eV.

Acknowledgments

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