Interpretation of the cosmic-ray energy spectrum and the knee inferred from the Tibet air-shower experiment.

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Abstract. **The origin of the knee is discussed based on the result of Tibet air-shower experiment over the wide energy range from 10^{14}eV to 10^{17}eV covering the knee region. The structure of the knee is interpreted through the comparison with recent direct observations and other air-shower experiments. It is shown that the cosmic-ray energy spectrum around the knee can be understood by two components, i.e., the first component is a global component whose energy spectrum extends over wide range with gradual change of the power index by approximately 0.4 in $10^{14}-10^{16}$ eV region. The second component exhibits a sharp knee at 4×10^{15} eV, which is characterized by its heavy mass and hard spectrum of a power**

index close to 2 with a cutoff feature suggesting its origin as nearby source(s).

***Keywords*: Knee, Acceleration of cosmic rays, SNR**

I. INTRODUCTION

A sudden steepening of the cosmic-ray energy spectrum around 4×10^{15}eV is called 'knee' where the value of the power index γ changes from approximately -2.7 to -3.1 when the energy spectrum is expressed by a power law $\propto E^{-\gamma}$. There has been a lot of works on the origin of the knee in terms of the acceleration mechanism [1], the propagation in the galaxy [2] or some nearby sources [3]. Another point of view is related to the nature of hadronic interactions [4]. Precise measurement of the energy spectrum and chemical composition of cosmic rays is required to resolve the cause of the knee. The Tibet AS$_\gamma$ Collaboration has measured the all-particle spectrum in a wide energy range between 10^{14}eV and 10^{17}eV by air-shower array of the area of 37000m^2 located at 4300m above sea level (Tibet, Yangbajing, China, atmospheric depth of 606 g/cm^2) and provided the most detailed spectrum around the knee [5]. The merit of the observation at high altitude is that the shower development reaches nearly maximum at the knee energy range leading to a good energy estimation. The study of the chemical composition has been also made with Tibet array using a core detector which measures the high energy electromagnetic component beyond TeV at the air-shower core [6]. Such high energy core can be produced by light primary nuclei (protons and helium) most efficiently because of the long interaction mean free path while the heavier nuclei dissipate primary energy rapidly high in the atmosphere. The prominent feature of these results is a sharp knee and steep spectra of the light components (proton and helium) suggesting a contribution of heavy components around the knee.

In this paper, a new interpretation of the knee is discussed based on the result of the Tibet experiment.

II. BROKEN POWER LAW SPECTRUM

The proton spectrum in the knee energy region obtained by the Tibet Hybrid Experiment (air-shower array + emulsion chamber + burst detector) is shown in Fig. 1 together with data by direct observations. Two interaction models of QGSJET01c and Sibyll2.1 are used to derive the proton flux whose model dependence is approximately 30%. It shows apparent steepening beyond 10^{14}eV and can be approximated by following broken power law formula.

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

where ε_b denotes the break point, γ the power index in the energy range $E << \varepsilon_b$ and the power index at $E >> \varepsilon_b$ is expressed by $\gamma + \Delta\gamma$. The function $h(E)$ is an empirically defined function as follows which describes the behavior at low energy region as explained by leaky box model [7].

$$h(E) = 1 - \exp[-(\frac{E}{a})^{1.3}] \qquad (2)$$

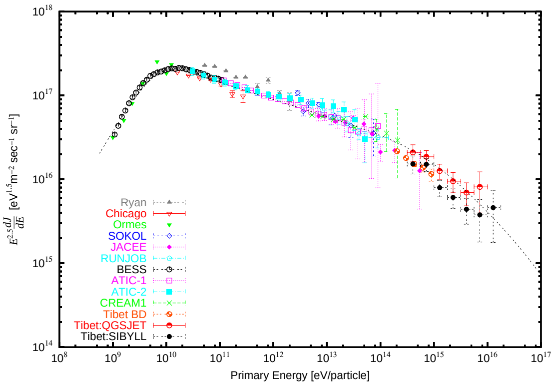

Fig. 1. Proton spectrum obtained by Tibet Hybrid Experiment and direct observations. Solid line is the broken power law spectrum with $\varepsilon_b = 7 \times 10^{14}$eV and $\Delta\gamma = 0.4$. See caption of Fig. 2 for cited data.

Since it is hard to precisely determine the value of two parameters ε_b and $\Delta\gamma$ only from this result because of the statistical accuracy and the systematic errors among different experiments, the spectra of all available elements measured by direct observations and all-particle spectrum measured by air-shower experiment are used to estimate these parameters under the assumption that each chemical component can be expressed by the broken power law formula eq. (1) with rigidity dependent break point, namely $\varepsilon_b(z) = z \times \varepsilon_b(p)$ is assumed, where z denotes the atomic number, while the value of $\Delta\gamma$ is assumed to be common to all elements. Then, the fitting is made so that the sum of each element should coinside to the all-particle spectrum including the energy range beyond the knee. The nuclei with odd atomic number is corrected using solar abundance as shown in Table I. From such overall fitting, we obtained $\varepsilon_b = (7 \pm 1) \times 10^{14}$eV for proton and $\Delta\gamma = 0.4 \pm 0.1$. The numerical values of fit parameters for each chemical component are listed in Table II. Fig. 2 shows the result of the overall fitting as mentioned above.

Odd Nuclei	Fraction
N/C	0.309
F/O	0.
Na/Mg	0.0167
Al/Si	0.0791
P/S	0.0104
Cl/Ar	0.010
K/Ca	0.0374
(Co+Ni+Cu+Zn)/Fe	0.059

TABLE I
RATIO OF THE NUCLEI WITH ODD AND EVEN ATOMIC NUMBERS IN SOLAR ABUNDANCES.

Z	Element	$E^{2.5}dj/dE$ at 10^{12} eV $\times 10^{17}$ eV$^{1.5}$m^{-2} sec^{-1} sr^{-1}	γ_z	a_z $\times 10^9$ eV
1	P	0.953±0.01	2.702± 0.004	5.49± 0.14
2	He	0.63±0.01	2.68± 0.009	16.3± 1.1
6	C	0.107±0.003	2.69± 0.02	53.8± 4.9
8	O	0.197± 0.007	2.66± 0.02	79± 10
10	Ne	0.050± 0.003	2.58± 0.03	65± 17
12	Mg	0.088± 0.004	2.72± 0.04	148± 22
14	Si	0.092± 0.004	2.72± 0.06	186± 34
16	S	0.023± 0.001	2.63± 0.04	231± 35
18	Ar	0.0126± 0.0009	2.57± 0.03	208± 45
20	Ca	0.0163± 0.002	2.66± 0.06	205± 66
	Sc,Ti,V,Cr	0.074± 0.002	2.87± 0.03	272± 24
26	Fe	0.200± 0.010	2.55± 0.02	288± 37

TABLE II
PARAMETERS OF THE ENERGY SPECTRUM FITTED TO THE DIRECT OBSERVATION DATA.

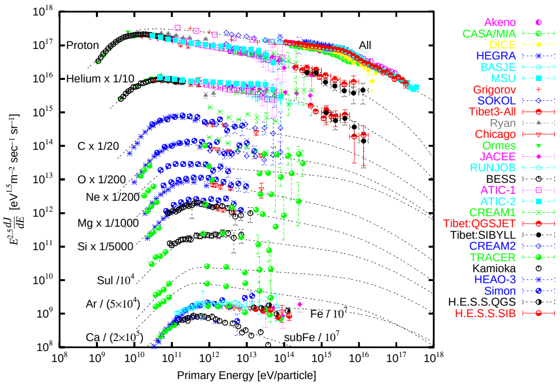

Fig. 2. Experimental data fitted by eq.(1). Cited data:Akeno [8], CASA/MIA [9], DICE [10], HEGRA [11], BASJE [12], MSU [13], Grigorov [14], SOKOL [15], Tibet3-All [5], Ryan [16], Chicago [17], Ormes [18], JACEE [19], RUNJOB [20], BESS [21], ATIC-1 [22], ATIC-2 [23], CREAM1 [24], Tibet:QGSJET and Tibet:SIBYLL [6], CREAM2 [25], TRACER [26], Kamioka [27], HEAO-3 [28], Simon [29], H.E.S.S.QGS and H.E.S.S.SIB [30]

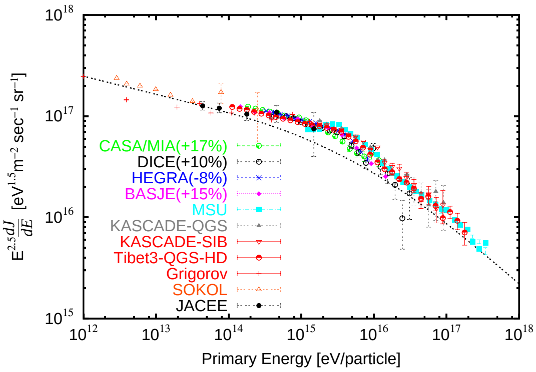

Fig. 3. All-particle spectrum normalized at 10^{15}eV to direct observations. Cited data: CASA/MIA [9], DICE [10], HEGRA [11], BASJE [12], MSU [13], KASCADE-QGS and KASCADE-SIB [31], Tibet3-QGS-HD [5] Grigorov [14], SOKOL [15],JACEE [19]

III. EXCESS COMPONENT AT THE KNEE

The all-particle spectrum beyond 10^{15}eV has been obtained by many air-shower experiments and all of them have shown the change of the spectral power index. However the detailed feature of the spectrum has not been obvious due to the limited covered energy range or statistics. The all-particle spectrum obtained by the Tibet AS$_\gamma$ Collaboration covers the wide range from 10^{14}eV to 10^{17}eV and makes it possible to argue the structure of the knee. In order to ensure the consistency among many air-shower data, they are normalized by shifting the energy to meet with the last point of JACEE around 10^{15}eV and shown in Fig. 3 together with a line obtained by overall fitting mentioned in section II (hereafter called global component). Fig. 3 shows that most of experimental data agree within statistical accuracy when systematic energy estimation errors are corrected by a factor within 20 % as shown in the parenthesis of the data title. Remarkable feature in this figure is the excess of the spectrum in the energy range between 10^{14} eV and 10^{16} eV over the global component. Subtracting the global component from all-particle spectrum we can see hard spectrum of power index close to 2, which is just the expected value of source spectrum before the modulation by the propagation, and it also shows cutoff feature as shown in Fig. 4 indicating that the excess component is due to the contribution of nearby source(s). The sharp peak of the excess component indicates that the chemical composition is not mixed as much as global component but its main component consists of elements with limited range of atomic numbers if we adopt the rigidity dependent acceleration limit. The result of Tibet data for proton and helium shows that the excess component is heavier than helium. One possible interpretation of the excess component is to attribute its origin to type Ia supernova (SN), whose ejecta contains heavy elements of calcium and iron group abundantly, because the energy spectrum of the excess component can be well reproduced by assuming the chemical composition of the type Ia SN ejecta, which could be injected to some nearby acceleration site.

IV. CONCLUSION AND DISCUSSION

Inferred from the proton spectrum obtained by the Tibet Hybrid Experiment, the energy spectrum of cosmic

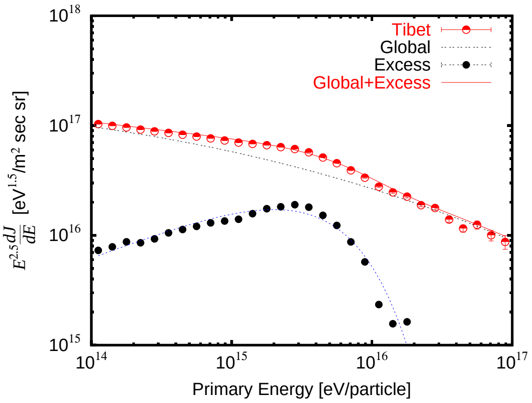

Fig. 4. All-particle spectrum around the knee. Solid line is the global component calculated by present model. Dashed line is the fit to the excess component seen in Tibet 3 data [5] which can be approximated as $f_x(E) \propto E^{-2}\exp(-E/4\mathrm{PeV})$. The dot-chained line is the sum of the global component and $f_x(E)$

rays over wide range is described as sum of the broken power law spectrum for each chemical composition. The break point for protons is estimated as $\varepsilon_b = 7 \times 10^{14}$eV, which might be related to the acceleration limit at the source region. A modeling of the energy spectrum of galactic cosmic rays based on multiple acceleration sites, which leads to the broken power law spectrum and discusses the maximum energy of the galactic cosmic rays, has been made by one of the authors [32] and reported in this conference. The meaning of ε_b is given there as the acceleration limit by type II supernova remnant (SNR) from the progenitor of 8 solar mass.

The sharp knee of the all-particle spectrum is interpreted by additional component from the nearby source(s). The chemical composition of the excess component has the feature of the type Ia SN ejecta. The possible explanation of the excess component is that the ejecta of type Ia SN(e) are injected to the nearby acceleration site(s).

In order to identify such local source, which might be a diffused one, it is interesting to investigate the primary gamma rays beyond multi TeV, which is the energy range of secondary gamma rays produced by interaction of nuclei of the energy ∼100TeV/nucleon at the source region. Such study can be made with capability of p/γ separation for the air-showers. In addition to the point search, it is possible to focus the direction of sources by observing γ-ray energy spectrum with wide solid angle. One can expect two kinds of γ-ray spectrum depending on the direction of the sky, one has broad knee for the direction of empty sky and another has sharp knee for the direction of the nearby source.

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REFERENCES

[1] Berezhko, E. G. & Ksenofontov, L. G. 1999, JETP **89**, 391-403, Stanev, T., et al., 1993, Astron. Astrophys. **274**, 902-908, Jokipii, J.R. 1987, Ap. J. **313** 842-846, Jokipii, J.R. 1982, Ap. J. **255**, 716-720, Kobayakawa, K., et al. 2002, Phys. Rev. D, **66**, 083004, Völk, H.J. & Zirakashvili, V. N. 2004, Astron. Astrophys. **417**, 807-817

[2] Ptuskin, V.S., et al., 1993, Astron. Astrophys. **268**, 726-735, Candia, J., et al., 2002, JHEP **12**, 33

[3] Erlykin, A. D., & Wolfendale, A. W. 2005, Astropart. Phys., **23**, 1-9
Bednarek, W. & Protheroe, R. J., 2002, Astrop. Phys. **16**, 397-409

[4] Nikolsky, S. I. & Romachin, V. A. 2000, Phys. Atomic Nucl. **63**, 1799-1814

[5] Amenomori, M et al, 2008, Astrophys. J, **678**, 1165-1179

[6] Amenomori, M et al, 2006, Phys. Lett. B **632**, 58-64

[7] Gupta,M. & Webber, W.B. 1989, ApJ, **340**,1124-1134

[8] Nagano, M., Hara, T., Hatano, Y., Hayashida, N., Kawaguchi, S., Kamata, K., Kifune, T., Mizumoto, Y. 1984, J. Phys. G, **10**, 1295-1310

[9] Glasmacher, M. A. K., et al. 1999, Astropart. Phys. **10**, 291-302

[10] Swordy, S.P. et al. 2000, Astropart. Phys. **13**, 137-150

[11] Arqueros, F. et al. 2000, Astron. Astrophys. **359**, 682-694

[12] Ogio, S., 2004, Astrophys. J., **612**, 268-275

[13] Fomin, Y.A. et al. 1991, Proc. 22nd ICRC, Dubrin, **2**, 85

[14] Grigorov, N.L., et al. 1971, Proc. 12th Int. Cosmic Ray Conf. (Hobart), **5**, 1746

[15] Ivanenko, I.P. et al., 1993, Proc. 23rd ICRC, Calgary, **2**, 17

[16] Ryan,M.J. et al., 1972, Phys. Rev. Lett., **28**, 985-988

[17] Swordy, P.S. et al. 1995, Proc. 24th ICRC, Rome, **2** 652, Mŭller, D. et al. Ap. J. 1991, **374**, 356-365

[18] Ormes, J.F. et al., 1965, Proc. 9th ICRC, London, **1**, 349, Webber, W.R. et al., 1965, Proc. 9th ICRC, London, **1**, 407

[19] Asakimori, K., et al. 1998, Astrophys. J., **502**, 278-283

[20] Apanasenko, A.V., et al. 2001, Astropart. Phys. **16**, 13-46

[21] Sanuki, T. et al. 2000, Astrophys. J. **545**, 1135-1142

[22] Ahn, H.S. et al. 2003, Proc. 28th ICRC, Tsukuba 1833,

[23] Wefel, J.P. et al. 2005, Proc. 29th ICRC, Pune **3**, 105

[24] Seo, E.S. et al. 2005, Proc. 29th ICRC, Pune **3**, 101

[25] Riccardo, Z. et al., 2007, 30th ICRC, Merida, **2**, 23-26

[26] Mŭller, D et al. 2005, Proc. 29th ICRC, Pune **3**, 89

[27] Kamioka, E. et al. 1997, Astropart. Phys. **6**, (2), 155-167

[28] Engelmann, J.J. et al. 1983, Proc. 18th ICRC, Bangalore, **2**, 17-20

[29] Simon, M. et al., 1980, Ap. J., **239**, 712-724

[30] Hofmann, W, 2005, Proc. 29th ICRC Pune, **10**, 97

[31] Antoni et al. 2005, Astropart. Phys. **24**, 1-25

[32] Shibata, M., 2009, Proc. 31st ICRC, Lodz, HE.1.2 icrc0295