29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Cosmic ray composition around the knee energy region

A.Bhadra and S. Sanyal

University of North Bengal, Siliguri, WB 734430 INDIA

Presenter: A. Bhadra (aru_bhadra@yahoo.com), ind-bhadra-A-abs4-he12-poster

Despite several efforts, the mass composition of cosmic rays around the knee region remains controversial. Here we critically examine the results obtained in various observations using different techniques to infer mass composition around the knee region.

1. Introduction

The primary cosmic ray energy spectrum is known to exhibit a power law behavior with a ‘knee ’around 3 PeV where the spectral index changes abruptly. The mechanism producing the knee is, however, still under discussion. An accurate determination of elemental composition of primary cosmic rays around the knee is expected to focus light on the origin of this interesting spectral feature.

Several Extensive Air Shower (EAS) measurements (till now the study of cosmic rays above 1 PeV is of indirect nature via the EAS observations) have been made to determine the mass composition of cosmic rays in the concerned energy region but the measurements have not yielded consistent results yet. Very recently employing improved analysis techniques and high-statistics data set, spectra for individual elements or mass group around the knee of the spectrum have been obtained from simultaneous measurements of different air shower observable [1, 2]. These results indicate that the knee is due to the steepening of proton/light elements spectra though it is also noticed that such a scenario of composition does not reliably describe the measurements over the whole energy region [2]. Since the knowledge of hadronic interactions, which is essential to interpret the observations in terms of primary mass end energy, is rather incomplete at present and the EAS parameters are subject to large intrinsic fluctuations, a conclusive resolution whether there is any change in the mass composition across the knee seems more meaningful at this stage. To infer such minimal but important feature on mass composition, in the present work we have critically examined the relevant results obtained in various observations worldwide.

2. Mass composition around the knee: observational scenario

A number of measurable properties of EAS are sensitive to primary mass. The basic strategy of determining chemical composition by EAS experiments is to observe such properties of EAS and to interpret the measurements in terms of primary mass using detailed Monte Carlo (MC) simulations. Depending upon the observable used, the study of mass composition by EAS technique may be divided into three broad categories: determination of composition via observation of Cerenkov radiation, via muon measurements, and via hadronic and/or electromagnetic (gamma families) components of air shower cores [3].

The position of the maximum development of electromagnetic component of EAS in the atmosphere roughly goes as $X_{max} \propto lnA$. The magnitude of EAS developmental fluctuations is also related to the primary mass. Proton initiated showers are expected to show greater fluctuations than heavy nucleus induced EAS. Experimentally X_{max} and its fluctuations can be estimated from the study of the Cerenkov radiation emitted by electrons in the atmosphere. The results of Cerenkov measurements by different experiments including the DICE [4], CASA-DICE [5], CASA-BLANKA [6], TUNKA [7], HEGRA [8], HEGRA-AIROBICC [9], SPACE-VULCAN [10], Yakutsk [11] and few others suggest for a mixed composition ($< lnA >= 1.5-2$) below the knee with either no significant change in average mass above the knee at least up to 10 PeV or a slowly decreasing/increasing average mass beyond the knee. A different conclusion is reached by only few experiments such as the CACTI [12].

The conclusions on mass composition from muon measurements are of divergent nature. Experiments like the CASA-MIA [13], HEGRA-CRT [14], KASKADE [15], EAS-TOP [16], SPASE-AMANDA [17], on the basis of muon content relative to electron content in EAS, infer that the composition becomes heavier with increasing energy in the region of knee whereas some other measurements such as the Haverah Park [18], Tien Shan [19], NBU [20] suggest for gradually decreasing average mass after the knee. Fluctuations of muon content in EAS with fixed electron size is also expected to depend on primary mass. Utilizing this property of EAS, MSU group [21] infers from their measurements that the composition is becoming heavier beyond the knee. On the other hand based on muon multiplicity distributions, underground experiments, such as the KGF [22], NUSEX [23], MACRO [24], SOUDAN [25], BUST [26] and few others, infer either for a unchanging mixed composition up to 10 PeV or a decreasing average mass through the knee. Recent results from the EASTOP-MACRO [1], based on multiplicity distribution of TeV muons in different shower size bins, however, suggest that average mass grows with energy beyond the knee. Latest KGF [27] observation supports such composition scenario. The KASKADE group has employed different improved analysis techniques to interpret the measurements made by their multi-detector set-up. In one such approach applying non-parametric techniques to the observed EAS data in an event-by-event basis they noticed that no significant change in the chemical composition occurs around the knee region [28]. But by unfolding the two-dimensional frequency spectrum of electron and muon numbers, the same group very recently obtained energy spectra for elemental groups [2] and their results indicate that the knee in the all particle spectrum is due to a steepening of the spectra of light elements; the heavy elements are practically absent in the all particle spectrum below 10 PeV.

Air shower cores (accompanied by EAS) contain a large fraction of primary energy, particularly in the early stage of shower development and are studied through observation of hadronic and/or electromagnetic (families of gamma rays produced by the decay of high energy neutral pions) components of the cores in emulsions/Burst detectors. The energy content in the shower cores is sensitive to the primary mass. The findings of emulsion experiments are, however, also divergent. While experiment PAMIR [29] indicates for light composition around the knee, Tibet ASγ [30] results lead to a heavy nuclei enriched composition at the knee. On the other hand Mt. Fuji [31], and Mt. Kanbala [32] data suggest for a mixed composition with no significant change in the average mass around the knee up to 10 PeV [33]. Mt. Chacaltaya observations [34] also support such composition scenario.

3. Discussion

As revealed from the discussion of the previous section that there is a consensus within the most Cerenkov observations that the composition remains practically unchanged with $< lnA >= 1.75 - 2$ around the knee. But the findings of muon measurements appears as divergent. If one restricts only to the underground muon measurements excluding the TeV muons, observations support the unchanging mixed composition scenario as emerged from the Cerenkov measurements. Results from analysis of TeV muons are, however, favor for heavier primaries beyond the knee. But TeV muons are generated from the decay of high energy pions produced in the non-central region of hadronic interactions and the knowledge of high energy interactions in the region is poor even at the accelerator energies owing to the geometry of the colliders. This seems reflected in the two KGF observations, which are not mutually consistent. The most of the muon measurements suffer from considerable uncertainties mainly due to insufficient area of muon detectors, low statistics of the data sample and systematic errors of the experiments in addition to the large intrinsic fluctuations of shower properties. In most cases an event-by-event analysis was not possible. Moreover, use of different air shower simulations to interpret measurements makes comparison between results difficult. When such uncertainties of the measurements are taken into account, results of most of the analysis based on muon content in showers do not contradict the constant composition scenario. The CASA-MIA findings of much heavier composition around the knee is not supported by other similar observations and a point to be mentioned that CASA-MIA group uses the MOCCA air shower simulation [35] to interpret their measurements whereas many of the others employ the CORSIKA [36]. The observations from emulsion measurements are also suited with fairly unchanging mixed composition except few like the Tibet measurements. Even the latest Tibet results indicate for proton domination up to the knee contradicting their earlier results.

4. Composition from size spectra

The most recent KASKADE observations based on the analysis of shower size spectra lead to a composition becoming heavier at and above the knee supporting the EASTOP-MACRO and some other results. The (fairly) unchanging mixed composition scenario as emerged from most of the observations is not supported by these recent results. In order to better understand the problem we analyze analytically (utilizing superposition model) the measurements on size spectra to estimate mass composition.
The electron and muon content in an EAS are related with primary energy as $N_i = a_i A \left(\frac{E}{A}\right)^{\alpha_i}$ where i stands for e (electron) or μ (muon). Here we exploited the simple superposition model. Hence if the primary energy spectrum obeys the power law behavior $n(>E) = n_o E^{-\gamma}$, the integral size spectrum of electrons and muons can be expressed as

$$n(>N_i) = n_o A^{-\gamma\left(1-\frac{1}{\alpha_i}\right)} \left(N_i/a_i\right)^{-\frac{\gamma}{\alpha_i}} \tag{1}$$

Therefore

$$n(>N_\mu)/n(>N_e) N_\mu^{-\frac{\gamma}{\alpha_\mu}} N_e^{\frac{\gamma}{\alpha_e}} = a_\mu^{\frac{\gamma}{\alpha_\mu}} a_e^{\frac{-\gamma}{\alpha_e}} A^{-\gamma\left(\frac{1}{\alpha_\mu}-\frac{1}{\alpha_e}\right)} \tag{2}$$

Clearly the above ratio will change with energy if either power indices of size spectra and/or A changes with energy. We note some advantages of using size spectra for determining mass composition over other techniques: 1) the mass dependence is much stronger, and 2) there is no need of simultaneous measurements of electrons and muons, combined precise measurements of electron and muon spectra by different experiments can provide information on composition.
The Eq. (2) has been utilized to infer variation of mass composition around the knee from the EAS-TOP observational data [16]. The analysis suggests for an unchanging mass composition in the range 0.1 to 10 PeV. The exact chemical composition of cosmic rays can not be determined just using Eq.(1) as a_i and α_i depend on the interaction picture adopted (the effects of a_i are particularly important). But combining the results of direct observations [37] (mixed primary composition with $< lnA >\sim 2$ below the knee), the present analysis indicates that composition remains mixed around the knee. However, the KASKADE observed size spectra cannot be consistently analyzed with the Eqs.(1) and (2) due to the fact that the difference in power index of the measured muon spectrum across the knee is smaller than that of the electron spectrum.

5. Conclusions

The results on chemical composition by most of the EAS measurements are found compatible with an unchanging mixed composition around the knee at least up to 10 PeV. We have restricted our analysis only around the knee and have not considered the composition above 10 PeV energy range. It is worth noting that all the mentioned measurements favor for a knee in the energy range 3 to 6 PeV.
The KASKADE observation of muon spectrum, however, cannot be explained with such composition scenario. In fact as already pointed out by different authors [38], the KASKADE observation on the change in slope of

electron spectrum at the knee cannot be consistently matched with that of the muon spectrum if a knee really exists in the primary spectrum. More observational results on muon size spectra from other experiments having large muon detector area, such as the GRAPES III [39], are required for better understanding the problem.

References

[1] M. Aglietta et al., Astropart. Phys. 20, 641 (2004)
[2] T. Antoni et al., Astro-ph/0505413, To appear in Astropart. Phys. (2005)
[3] A. Haungs et al., Rep. Prog. Phys. 66, 1145 (2003)
[4] K. Boothby et al., Astrophys.J 491, L35 (1997)
[5] S. P. Swordy et al., Astropart. Phys. 13, 137 (2001)
[6] J. W. Fowler et al., Astropart. Phys. 15, 49 (2001).
[7] D. Cherev et al., astro-ph/0411139.
[8] A. Karle et al., Astropart. Phys. 3, 321 (1995)
[9] F. Arqueros et al., Astron. Astrophys. 359, 682 (2000)
[10] J. E. Dickinson et al., 26th ICRC 3, 136 (1999)
[11] N. N. Efimov et al., Proc. Int. Symp. astrophysical aspects of most energetic cosmic rays, Ed. M. Nagano, and F. Takahara, p 20 (1991).
[12] S. Paling et al., 25th ICRC 5, 253 (1997)
[13] M. Glasmacher et al., Astropart. Phys. 12, 1 (1999)
[14] K. Bernlohr et al., Astropart. Phys. 5, 139 (1999)
[15] J. Weber et al., 26th ICRC 1, 341 (1999)
[16] G. Navarra et al., Nucl. Phys. B (Proc. Suppl.) 60B, 105 (1998)
[17] K. Rawlins et al., 28th ICRC 1, 173 (2003)
[18] P. R. Blake and M.F. Nash, J. Phys. G: Nucl. Part. Phys. 24, 217 (1998); *ibid* 21, 1731, (1995)
[19] E. V. Danilova et al., 24 ICRC, 1, 286 (1995)
[20] C. Chakrabarty et al., IL Nuovo Cim. 21, 215 (1998)
[21] Y. Fomin et al., J. Phys. G: Nucl. Part. Phys. 22, 1839 (1996)
[22] B. S. Acharya et al., 18th ICRC 9, 191 (1983)
[23] M. Aglietta et al., Nucl. Phys. (Proc. Supl.) 14B, 193 (1990)
[24] S. Ahlen et al., Phys. Rev. D 46, 4836 (1992)
[25] S. Kasahara et al., Phys. Rev. D 55, 5282 (1997); N. Longley et al., Phys. Rev. D 52, 2760 (1995)
[26] V. N. Bakatanov et al., Astropart. Phys. 12, 19 (1999)
[27] H. R. Adarkar et al., Phys. Rev. D 57, 2653 (1998)
[28] T. Antoni et al., Astropart. Phys. 16, 245 (2002)
[29] J. Malinowski et al., 28th ICRC, 1, 135 (2003); A.S. Borisov et al., 28th ICRC, 1, 111 (2003)
[30] M. Amenomori et al., Phys. Rev. D 62, 072007 (2000)
[31] M. Akashi et al., Nuovo Cim. A 65, 355 (1981)
[32] J. R. Ren et al., Nuovo Cim. A 65, 355 (1981)
[33] C. Costa et al., Phys. Rev. D 54, 5558 (1996); J. Huang et al., Astropart. Phys. 18, 637 (2003)
[34] C. Aguirre et al., Phys. Rev. D 62, 032003 (2000)
[35] A. M. Hillas, 19th ICRC 1, 155 (1985)
[36] D. Heck et al., Forschungszentrum Karlsruhe FZKA 6019 (1998)
[37] A. V. Apanasenko et al., Astropart. Phys. 16, 13 (2001); K. Ashakimori et al, 24 ICRC, 2, 707 (1995)
[38] Y. V. Stenkin, astro-ph/0410574; Mod. Phys. Letts. A 18, 1225 (2003); N. P. Il'ina et al., 28th ICRC 1, 123 (2003)
[39] S.K. Gupta et al., Nucl. Instr. & Meth. A 540, 311 (2005).