ENERGY SPECTRA OF HADRONS IN THE ATMOSPHERE AND THE MASS COMPOSITION

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Abstract

Detailed calculation of the flux of cosmic ray hadrons in the atmosphere is performed under the assumption that the inelasticity coefficient in hadron-air nucleus collision remains energy independent up to energies around 10^{16} eV.

The predicted fluxes agree very well with the observed ones when it is assumed that the cosmic ray composition remains constant up to the energies a few times 10^{15} eV and that the total cosmic ray flux is such as deduced from extensive air shower / EAS / observations.

Lecture based on the paper [4].

1. Introduction

In the present work an attempt is made to verify certain hypothesis about primary particle mass composition from the observation of the secondary hadrons in the atmosphere.Due to the fact that the basic properties of high energy interactions are now known up to the energies exceeding 10^{14} eV the accurate data on intensities of hadrons in the atmosphere can be used for evaluating the properties of high energy primary cosmic rays.In particular those data can be used for verification of above mentioned hypothesis concerning the energy spectrum and mass composition at energies around 10^{15} eV.

The important point which should be stressed here is that the detectors used in deriving the energy spectra of hadrons in the atmosphere are in every aspect superior to the detectors used in direct observations of the primary cosmic rays of comparable energies.Their area and detection time are by orders of magnitude bigger and the particle energy is determined by calorimetric method application of which practically is not possible in the detectors flown in satelites and balloons.If those advantages are combined with moderately good understanding of cosmic ray propagation in atmosphere the obtained results could be even more reliable than most of the direct observations.For instance the direct observations are based on thin calorimeters; in those calorimeters the estimation of energy critically depends on the value of the inelasticity coefficient for π° production.The SPS data clearly seems to indicate that that coefficient decreases when the primary particle energy increases.

It seems that even at the same energies the indirect methods are competitive to the direct observations / at least as a tool for verification/ but due to the powerful collection power those methods can be used at much higher energies.

2. The primary cosmic ray energy spectrum and mass composition at energies above 10^{14} eV

Direct measurements of the energy spectra of various nuclei have been performed up to the energies approaching 10^{14}

eV.The information about the spectra above that limit are obtained by various indirect methods.Those methods however give answers which strongly depend on the assumptions about properties of high energy hadron interactions.If the validity of the Feynman scaling is assumed it is obtained that the experimental data can be moderately well described only under the assumption that the primary flux is dominated by very heavy nuclei - practically it would have to be pure iron. Detailed analysis of the cosmic ray showers however showed that the showers in generral look very different from those expected from heavy primaries.That fact leads to the conclusion about serious violation of the scaling.The conclusion has been subsequently confirmed by accelerator data from proton - antiproton collider.The question of the scaling validity at higher energies is however still open.

In the present work,as it was stated above,we try to discuss that question using the data on flux of high energy hadrons in the atmosphere.The sensitivity of the hadron flux to the mass composition arises from the fact that it is determined by the energy spectra of nucleons whwereas most of the observations gives energy spectrum of nuclei.

In the analysis we try to distinguish between the heavy dominated composition and the normal mixed composition obtained by extrapolation from lower energies.As the heavy dominated composition we have taken so called Fuji composition [1] obtained from the frequency of the γ - ray families and less extreme Akeno spectrum [2] used in analysis of EAS data in Akeno.The normal mixed composition, termed "constant - mass composition CMC", was obtained by an extrapolation of the directly measured spectra of various particles with a single constant differential slope, $\gamma=2.7$, up to $2\cdot10^{15}$ eV for protons and to the point of the same rigidity for every group of nuclei.The slope then increases to $\gamma=3.0$.The normalisation coefficients and breaking points for all componenets are summarised in table 1.A_1 is the normalisation coefficient below the A_2 that above the breaking point.

Those three spectra in function of energy per nucleus are given in figuer 1 and in function of energy per nucleon are

Table 1.

	A_1	E_0/eV/	A_2
p	1.72 10^4	2 10^{15}	1.34 10^6
He	9.20 10^3	4 10^{15}	8.80 10^5
CNO	6.20 10^3	14 10^{15}	8.63 10^5
H + VH	9.20 10^3	26 10^{15}	1.54 10^6
Fe	6.20 10^3	52 10^{15}	1.28 10^6

Note. The spectrum is represented by $A_1 \cdot E^{-2.7}$ for $E < E_0$ and $A_2 \cdot E^{-3.0}$ for $E > E_0$. The units of A are / m^{-2} s^{-1} sr^{-1} GeV^{-1} /.

given in figure 2. In figure 1 there is also given the spectrum deduced from EAS observations by Wdowczyk [3]. The differences between those two methods of presentation are clearly seen. Those differences guarantee that the observations of the flux of hadrons can distinguish between various assumptions about the primary mass composition.

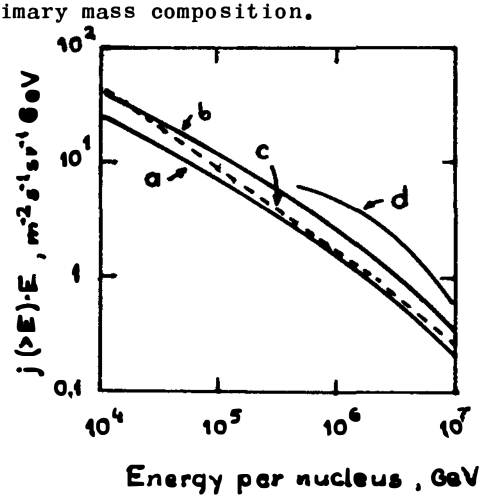

Figure 1. The integral energy spectra of nuclei for three different mass composition : a - Fuji spectrum, b - Akeno spectrum, c - present work CMC, d - EAS spectrum.

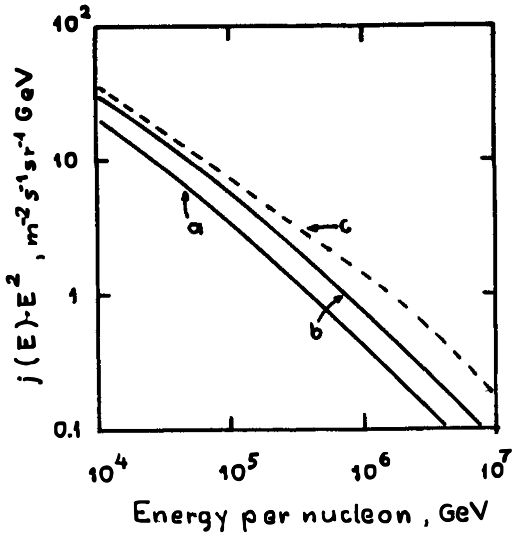

Figure 2. The differential nucleon energy spectra for three mass compositions considered here / a,b, c - as in figure 1 /.The CMC spectrum is represented by $2.3\ 10^4 \cdot E^{-2.7}$ up to about $2 \cdot 10^{15}$ eV.

3. The experimental and predicted spectra of hadrons in the atmosphere

It has been demonstrated [4] that the fluxes of hadrons in the atmosphere from various experiments agree relatively well /when corrected for the difference in the hight of the observation levels /. In the figure 3 there are plotted data from two experiments [5,6] which may be considered as the most accurate in their classes but which differ very significantly in respect to the method of detection / ionisation chamber calorimeter and γ - ray film chamber /. Very good agreement of the two sets of data is reassuring.

Comparison with the predicted curves shows that the heavy dominated compositions are ruled out.The data are reproduced only in the case when the normal composition is taken and the

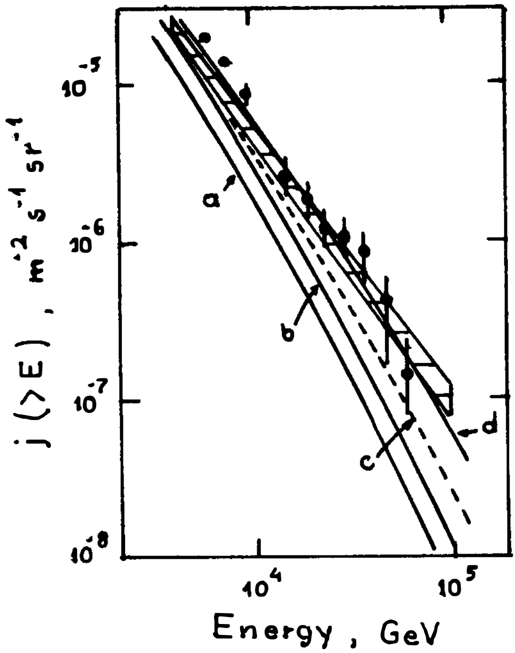

Figure 3. The measured and predicted spectra of hadrons at Mount Fuji level. [hatched band] - Akashi et al [6], ɸ - Nikolski [5]/ converted to the Mount Fuji level /.The predicted spectra are shown for the three mass compositions and energy spectra considered / a,b,c - as in figure 1/. The EAS predictions are obtained assuming the same mass composition as in the CMC model.

total flux is increased to match the total flux deduced from EAS observations.

If the primary flux was enriched in protons the absolute intensity could be reduced.

4. The surviving protons in the atmosphere

The data on unaccompaning hadrons / surviving protons / can be used as some sort of cross - check of the accuracy of hadron measurement in the atmosphere.Now when the energy de-

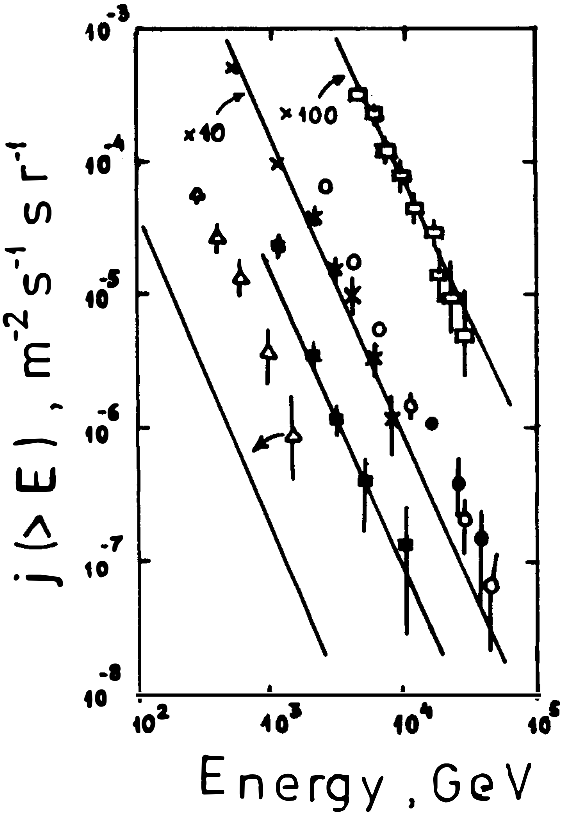

Figure 4. The integral energy spectra of the surviving protons at different levels of the observations.
ф - Mount Chacaltaya 5200 m [7], ⳾,ɸ,ф - Tien Shan 3330m[9,10,11], ф - Aragass 3200 m [8], ♆ - sea level [12]. Full lines - predicted spectra of the surviving protons for considered altitudes / note that the Chacaltaya intensities are multiplied by factor 100 and the Tien Shan by 10 for the better see /.

pendence of the cross - section in of hadrons interaction is known from measurements in SPS and the cosmic ray proton energy spectrum is measured rather accurately we can predict the surviving proton fluxes at various depths. In figure 4 the predicted fluxes are compared with the observations.Rather good agreement is seen except for the sea level observation. The discrepancy at sea level is however understandable if we remember that the presented data were collected using rather small calorimeter and EAS device and that the sea level flux of surviving protons is small.It should be also noted that at sea level the small showers originated very high in the atmosphere could be already undetectable.

5. Conclusion

The intensity of cosmic ray hadrons at the moutain altitude level clearly contradicts the assumption about significant increase of the average mass of the primary cosmic rays at energies around 10^{15} eV.It seems that whatever the mass composition of cosmic rays at that energies is the intensity of protons is moderately high since the flux of nucleons is predominatly determined by the intensity of primary protons.

The significant flux of primary protons together with various observations of the properties of secondary cosmic rays prove that serious deviations from the Feynman scaling hypothesis exists up to energies around 10^{15} - 10^{16} eV.

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