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THE COSMIC RAY PROTON SPECTRA AT DIFFERENT ATMOSPHERIC DEPTHS DERIVED FROM THE RECENT PRIMARY SPECTRUM OF OLEJNICZAK ET AL.

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The differential proton spectra at different atmospheric depths have been calculated from the recent primary cosmic ray spectrum of Olejniczak, Wdowczyk and Wolfendale by using the conventional phenomenological model after Ashton. The energy dependence of the nucleon nucleus interaction cross section is assumed in the calculations. The estimated proton spectra at atmospheric depths 535, 690, 990 and 1033 gcm^{-2} fits well the experimental proton spectra of Allkofer and Kraft, Kocharian et al., Fickle and Lamb, Brooke and Wolfendale, Diggory et al. and the results yield an energy dependence of nucleon elasticity in the spectral range 20—100 GeV.

1. Introduction

The primary cosmic ray particles are assumed to be directly accelerated in the cosmic ray sources and the secondary nuclei are produced predominantly by spallatian reactions of the primary particles with the nuclei in the atmosphere. Comparing the measured spectrum of primary cosmic ray particles with the spectra of cosmic ray protons measured at various atmospheric depths, one can predict the validity of the interaction models and their various reaction parameters.

In an earlier investigation one of us[1] has found that the constant energy model of Brooke et al.[2] can be successfully used to derive the sea level muon spectrum from the primary cosmic ray spectrum of Grigorov et al.[3] if the energy dependence of the pion inelasticity K_π is taken into account. The energy dependence of K_π is also supported by our other investigation[4] where Cocconi-Koester-Perkins model[5] was used to correlate the primary nucleon intensity with the sea level muon spectrum.

In the present paper we have related the composite primary cosmic ray spectrum of Olejniczak et al.[6] to the measured proton spectra at depth 535 gcm^{-2} (Allkofer and Kraft[7]), 690 gcm^{-2} (Kocharian et al.[8]), Fickle and Lamb[9] at depth 990 gcm^{-2} and 1033 gcm^{-2} (Brooke and Wolfendale[10], Diggory et al.[11]), using an energy dependent proton elasticity parameter in the conventional phenomenological model after Ashton[12].

2. *Formulation*

Let ω be the probability that a nucleon after making an inelastic collision with an air nucleus emerges from the collision in different charge state then the mode of production of proton and neutron in such collision will be given by

$$P_o + \text{air nuclei} \rightarrow n\,(=\omega P_o) + P\,(=\overline{1-\omega P_o})$$

$$N_o + \text{air nuclei} \rightarrow P\,(=\omega N_o) + n\,(=\overline{1-\omega \mathrm{N}_o}) \qquad (1)$$

where P_o and N_o are the primary proton and neutron numbers, respectively.

From the above consideration it is evident that the proton excess after z successive inelastic collisions is as given by Ashton[12],

$$\delta_z = \frac{P_o - N_o}{P_o + N_o}(1-\omega)^z = \delta_o (1-2\omega)^z \qquad (2)$$

assuming that the primary nucleon spectrum at the top of the atmoshpere usually consists of 83% proton and 13% neutron and $z = x/\lambda$, where x is the atmospheric depth and λ is the mean interaction length.

If the integral energy spectrum of primary nucleons obeys a power law fit of the following form

$$N(>E) = B\,E^{-(\gamma-1)} \qquad (3)$$

the contribution to proton excess after r inelactic collisions will be

$$B\,(E/\beta^r)^{-(\gamma-1)} \cdot \frac{\mathrm{e}^{-z} z^r}{r!}\,\delta_0\,(1-2\omega)^r \qquad (4)$$

where β ih the nucleon elasticity in nucleon-air nucleus interactions and $P(r) = \mathrm{e}^{-z} z^r/r!$ is the probability that a nucleon makes r collisions, if the mean is z.

Again the differential energy spectrum of nucleons at a depth x gcm^{-2} in air can be calculated after Ashton[12] as

$$N(E)\,\mathrm{d}E = \sum_{r=0}^{\infty} A\,(E/\beta^r)^{-\gamma}\,\frac{\mathrm{d}E}{\beta^r}\,\frac{\mathrm{e}^{-z}\,z^r}{r!} =$$

$$= A \exp\left[-x\,(1-\beta^{\gamma-1})/\lambda\right] E^{-\gamma}\,\mathrm{d}E = A \exp\left[-\,x/\Lambda\right] E^{-\gamma}\,\mathrm{d}E \qquad (5)$$

where $\Lambda = \lambda/(1-\beta^{\gamma-1})$ is the mean absorption length of the nucleons and $A\,E^{-\gamma}\,\mathrm{d}E$ represents the differential primary nucleon spectrum.

The analysis of the direct measurement of the energy spectrum of mass composition of primary cosmic ray particles and the associated problems of the mass composition by Olejniczak, Wdowzcyk and Wolfendale[6] (to be referred to as OWW spectrum) yield a composite primary spectrum of cosmic ray particles. Later Popova[13] formulated the composite spectrum of the primary particles proposed by OWW which is found to follow the form:

$$N(E)\,\mathrm{d}E = (0.155\,E^{-2.6} + 0.190\,E^{-2.6} + 0.34\,E^{-2.6} + 0.266\,E^{-2.6} +$$

$$+ 0.551\,E^{-2.6})\,\mathrm{d}E = 1.90\,E^{-2.6}\,\mathrm{d}E \qquad (6)$$

where E is the nucleon energy expressed in GeV and $N(E)\,\mathrm{d}E$ is the differential primary intensity expressed in (cm^2 sec sr GeV)$^{-1}$ units. The above relation represents the contribution to the energy spectra of five groups of primary cosmic ray particles with the following atomic numberss: 1, 4, 10, 26 and 56. Hence the spectral amplitude is A which equals 1.9 and the spectral index γ being 2.6, respectively.

Thus the expected proton excess at an atmospheric depth x gcm^{-2} is

$$\delta_x = \frac{B E^{-(\gamma-1)}\,\mathrm{e}^{-z}\,\delta_0 \left[1 + \beta^{\gamma-1}\,\frac{(1-2\omega)}{1!}\,z + \beta^{2(\gamma-1)}\,\frac{(1-2\omega)^2}{2!}\,z^2 + ..\right]}{B \exp\left[-z\,(1-\beta^{\gamma-1})\right] E^{-(\gamma-1)}} =$$

$$= \delta_0 \exp\left[-\,2\,x\beta^{\gamma-1}\,\omega/\lambda\right] \qquad (7)$$

where $B \exp[-z\,(1-\beta^{\gamma-1})]\,E^{-(\gamma-1)}$ is the integral nucleon spectrum at a depth x gcm^{-2}.

Since the mean interaction length λ decreases with the increase of nucleon energy E as suggested by Grigorov et al.[14] and follows the relation

$$\frac{1}{\lambda} = \frac{1}{\lambda_0}\,(1 + a \ln (E/E_0)) \qquad (8)$$

where $E_0 = 20$ GeV, $a = 0.0369 \pm 0.0074$, $\lambda_0 = 84$ gcm^{-2}, the nucleon elasticity β is found to be energy dependent as a consequence of relation $\Lambda = \lambda/(1-\beta^{\gamma-1})$ and Λ is constant. The energy dependence of β is observed to follow the relation

$$\beta \cong a + b \ln E \qquad (9)$$

where a and b are constants.

Hence the differential proton spectrum at an atmospheric depth x gcm^{-2} will finally become

$$N(E)\,\mathrm{d}E = \frac{1+\delta_x}{2}\exp(-x/\Lambda)\,A\,E^{-\gamma}\,\partial E \qquad (10)$$

where δ_x has to be calculated by evaluating α and β values from the relation (7) and (8) for corresponding E values.

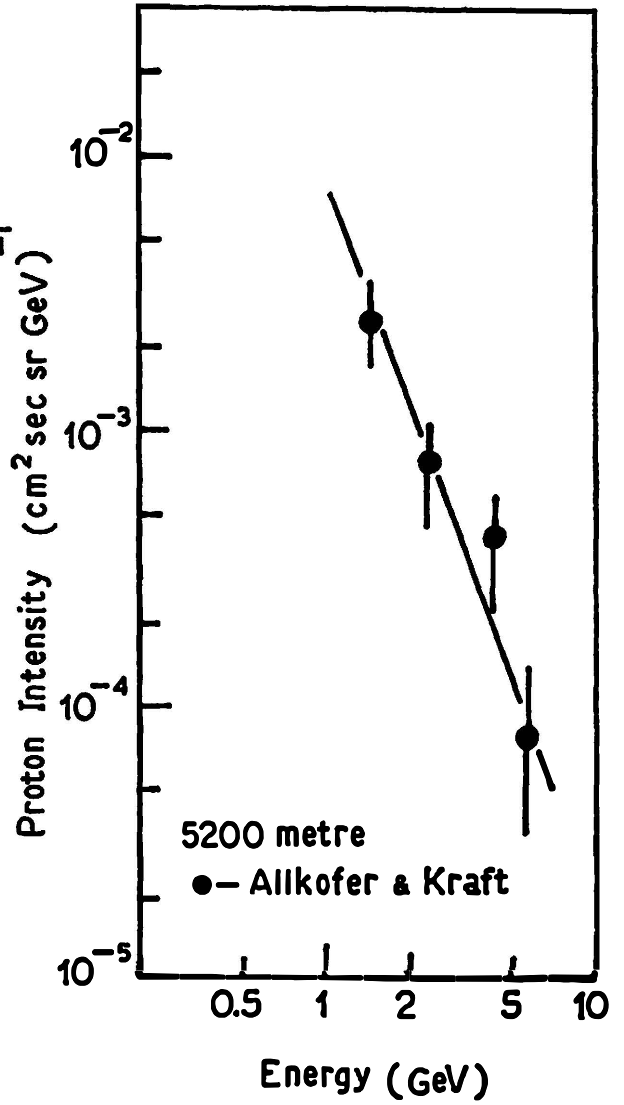

Fig. 1. The cosmic ray proton spectrum at an altitude 5200 metre (atm. depth 535 gcm^{-2}): The full curve represents the theoretical spectrum — Present Work; Experimental data:0 — Allkofer and Kraft[7].

3. Results and discussions

The primary cosmic ray spectrum at the top of the atmosphere is taken from the power law fit to the measured cosmic ray primary intensity data of Olejniczak et al.[6].These nucleons interact with the air nuclei producing protons, neutrons and mesons. Calculation of proton excess at different successive interactions has been made to estimate the proton spectra at different atmospheric depths. The derived spectra at different altitudes have been calculated. The derived spectra at different atmoshperic depths have been displaced in the Figures 1, 2, 3 and 4. The estimated proton spectra agree approximately with the experimental data of Allkofer and Kraft[7], Kocharian et al.[8], Fickle and Lamb[9], Brooke and Wolfendale[10] and Dig-

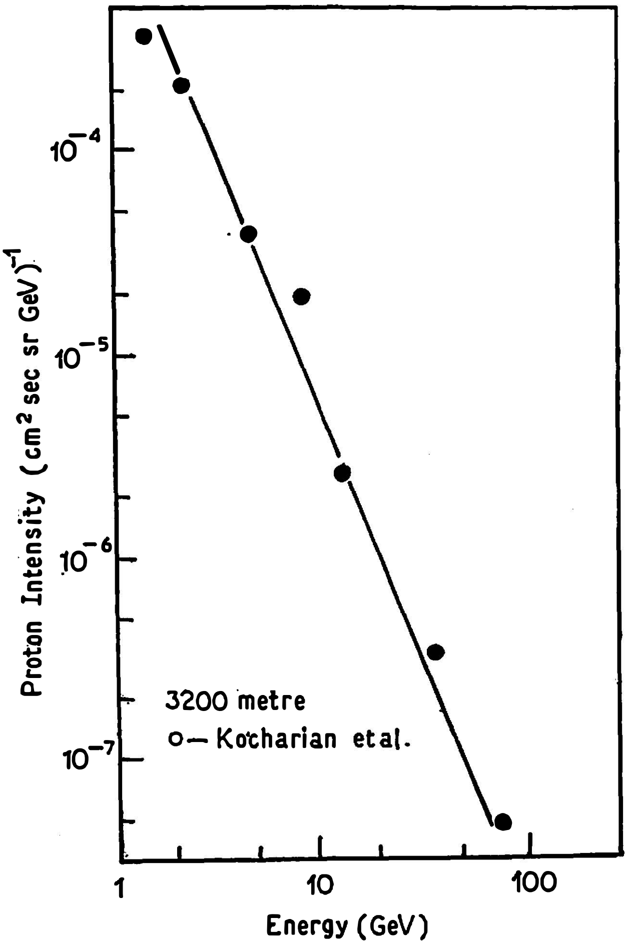

Fig. 2. The proton spectrum at an altitude 3200 metre (atm. depth 690 gcm^{-2}). The full curve represents the theoretical spectrum — Present Work; Experimental data: 0 — Kocharian et al.[8].

gory et al.[11] when an energy dependence of nucleon elasticity is assumed in the calculation for above 20 GeV proton energy. Below this energy the value of β is found to be constant of value and is about 0.422.

The inelastic nucleon-nucleus interaction cross section increases with the energy of primary nucleons. As $\sigma_{in.} \sim 1/\lambda$, the interaction length decreases with the increase of energy E of primary nucleons: the coefficient α is taken to be $0.0369 \pm \pm 0.0074$ as suggested experimentally by Grigorov et al.[14] in the energy range 20—2000 GeV.

The increase in nucleon elasticity β with the increase in primary nucleon energy E is observed as a consequence of the relationship $\Lambda = \lambda/(1 - \beta^{\gamma-1})$. The nucleon elasticity β increases with the increase of primary nucleon energy in the range 20—100 GeV and obeys the following relation

$$\beta \cong 0.353 + 0.024 \ln E. \qquad (11)$$

This is consistent with the decrease of pion elasticity as suggested in our earlier investigations[4] via CKP model[5].

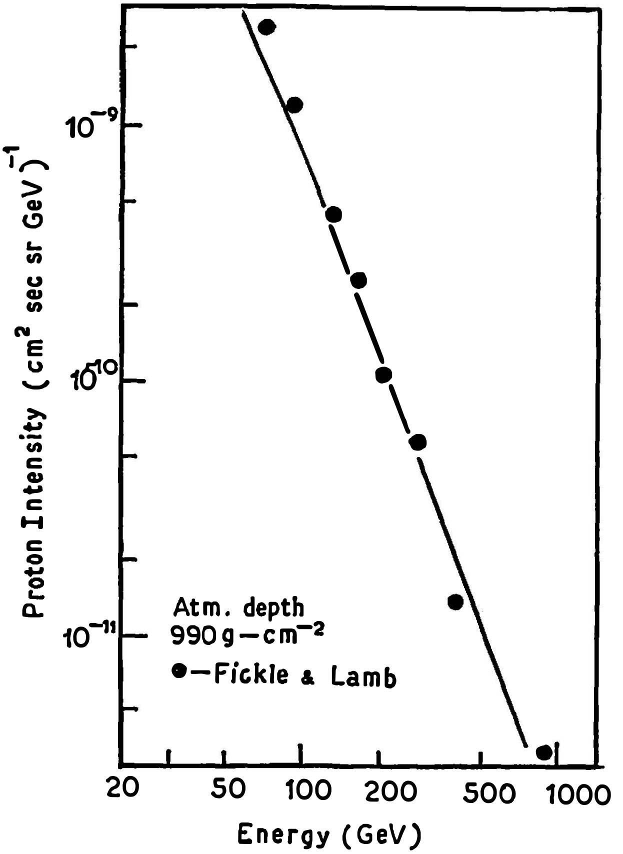

Fig. 3. The proton spectrum at an atmospheric depth 990 gcm^{-2}. The full curve represents the theoretical spectrum — Present Work; Experimental data: 0 — Fickle and Lamb[9].

4. *Conclusion*

The phenomenological model of Ashton[12] can be used to derive the proton spectra at different atmospheric depths from the primary cosmic ray spectrum of Olejniczak, Wdowczyk and Wolfendale[6] when the nucleon elasticity β and inelastic nucleon-nucleus interaction cross section are found to increase with energy E in the energy range 20—200 GeV. This fact supports the increase in pion-inelasticity with energy[4]. The decrease of nucleon-inelasticity $K_T = 1 - \beta$ with energy suggests that the secondary nucleons emitted in pp inelactic interactions share less energy from primary nucleons at high energies.

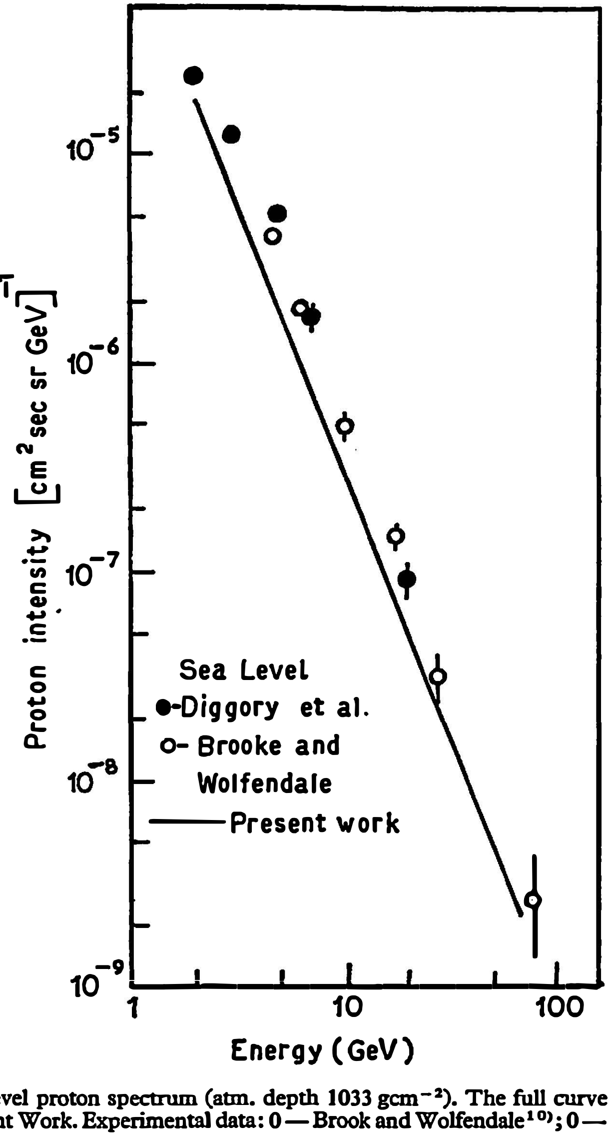

Fig. 4. The sea level proton spectrum (atm. depth 1033 gcm^{-2}). The full curve is the calculated spectrum — Present Work. Experimental data: 0 — Brook and Wolfendale[10]; 0 — Diggory et al.[11].

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PROTONSKI SPEKTAR KOZMIČKIH ZRAKA NA RAZLIČITIM ATMOSFERSKIM DUBINAMA IZVEDEN IZ PRIMARNOG SPEKTRA OLEJNICZAKA I SURADNIKA

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Diferencijalni protonski spektar na različitim atmosferskim dubinama izračunat je iz nedavno dobijenog primarnog spektra kozmičkih zraka Olejniczaka, Wdowczyka i Wolfendale-a koristeći konvencionalni fenomenološki model po Ashtonu. Energetska zavisnost poprečnog presjeka interakcije nukleona sa jezgrom je pretpostavljena u računima. Procijenjeni protonski spektar na atmosferskim dubinama 535, 690, 990 i 1033 gcm^{-2} dobro se slaže sa eksperimentalnim protonskim spektrom Allkofera i Krafta, Kochariana et al., Fickle-a i Lamba, Brooke-a i Wolfendale-a, Diggory-a et al., i rezultati daju energetsku zavisnost nukleonskog elasticiteta u spektralnom intervalu 20—100 GeV-a.