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DERIVATION OF ALL PARTICLE PRIMARY COSMIC RAY SPECTRUM AND THE CONVERSION FACTORS AT SUPER HIGH ENERGIES

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The all particle primary spectrum and conversion factors of elemental fluxes at different energies have been estimated from the recent direct measurements of proton and helium intensity data of Japanese American Cooperative Emulsion Experiments and nuclei intensity data of Abulova et al. at balloon altitudes. The superposition method has been used for the estimation of nucleon flux from the spectra of different nuclei. The calculated differential nucleon flux follows the form

$$N(E)\,\mathrm{d}E = 2.36 \times 10^{4}\, E^{-2.7}\, \mathrm{d}E\,(\mathrm{m}^2\ \mathrm{s\ sr\ GeV/nucleon})^{-1}$$

in the spectral range $10^3 - 10^6$ GeV. The proton-nucleon and neutron-nucleon conversion factors have been estimated and the values are 0.74 and 0.13, respectively. The conversion factors for protons-nuclei and nucleons-nuclei follow the forms $0.921\, E^{-0.1}$ up to 10^6 GeV energy. The derived all particle primary spectrum after the nuclear fragmentation method follows the form

$$N(E)\,\mathrm{d}E = 1.9 \times 10^{4}\, E^{-2.6}\, \mathrm{d}E\,(\mathrm{m}^2\ \mathrm{s\ sr\ GeV/nucleus})^{-1}$$

which is in approximate agreement with those of proton satellite ionisation calorimeter data of Grigorov et al. and Chacaltaya air shower data of La Pointe et al. in the energy range $10^2 - 10^6$ GeV.

1. Introduction

The information about the chemical composition of high energy cosmic rays is of phenomenological importance in high energy astrophysics.

Earlier Hayakawa[1] has shown that the integral primary cosmic ray spectrum follows a power law fit which is of the form

$$I(> E) = 1.0 \times E^{-1.6} \text{ per } (\text{cm}^2 \text{ s sr})$$

where E is the total energy in GeV. Later Grigorov et al.[2] have determined the all particle primary spectrum from the satellite borne ionisation calorimeter experiments and found a change in the primary proton spectral index viz. $\gamma_p = 1.7$ to 2.5 beyond 1 TeV energy. Ryan et al.[3] also determined the primary proton and helium spectra up to 2 TeV energy using balloon borne ionisation calorimeter as detector. They found no break in the spectral index of integral primary proton spectrum as has been recorded in the measurements of Grigorov et al.[2]. The recent measurements of Schmidt et al.[4] and Simon et al.[5] yield the precise spectral shapes of different cosmic ray nuclei at energies below 1 TeV energy. More recently Abulova et al.[6] confirm the definite spectral shapes of three groups of primary nuclei and supported the findings of Simon et al.[5] rather at higher energies. Erlykin (private communication) has pointed out that nuclei-proton flux ratio is closer to 3 at 100 GeV energy. The balloon borne emulsion calorimeter experiments of Japanese American Cooperative Emulsion Experiments[7] (to be referred to as *JACEE*) gave the proton and helium spectra at super high energies. In the present work we have used *JACEE* proton and helium intensity data along with the nuclei spectra of Abulova et al.[6] to estimate the energy dependence of conversion factors of different primary particles. The total primary spectrum has been estimated by using superposition method and the results is compared with earlier available satellite measured data of Grigorov et al.[2] and Chacaltaya air shower results of La Pointe et al.[8].

2. Experimental spectra

The *JACEE* data on the proton and helium have been considered in the present investigation. Fig. 1 shows the plot of proton and helium intensity data multiplied by $E^{1.7}$ displayed as functions of energy E. The recent measurements on the chemical composition of primary cosmic rays of Abulova et al.[6] confirms the differential nuclei intensity data of Simon et al.[5] satisfactorily and the product of the differential nuclei intensity and $E^{2.7}$ for three groups of nuclei viz. medium $M (Z = 6 - 9)$, heavy $H (Z = 10 - 19)$ and very heavy $VH (Z \geqslant 20)$ have been plotted in Fig. 2.

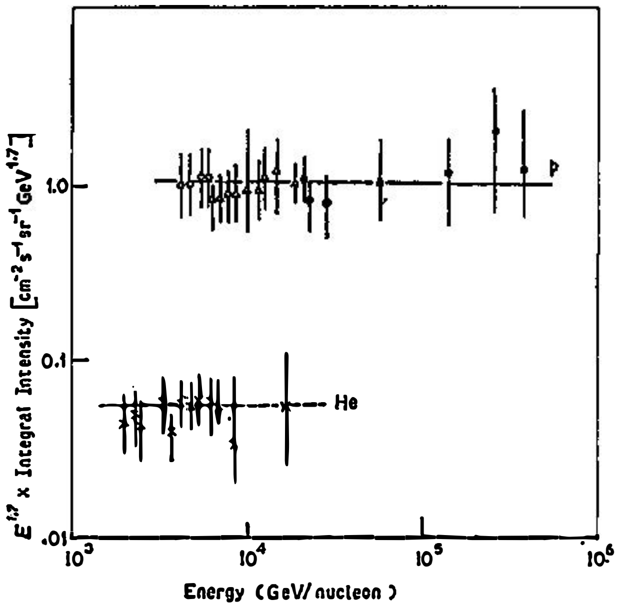

Fig. 1. Integral energy spectra of protons and helium: *JACEE* data[7] ○, △, ● — protons; x-helium. Full and broken lines drawn through the data are the fits after relations (5) and (6) for the intensities of protons and helium, respectively.

3. *Nuclear physics*

We assume that the differential spectra of protons, helium and a mixture of heavier nuclei follow power laws of the form

$$n_i(E)\,\mathrm{d}E = K_i\,E^{-(\gamma_i+1)}\,\mathrm{d}E \tag{1}$$

where K_i and γ_i are the spectral amplitudes and indices of the primary fluxes.

The model of nuclear fragmentation shows that the hadronic cascade produced by a cosmic ray nucleus of atomic weight A and total energy E is treated as the superposition of A cascades produced by primary nucleons of energy $E_N = E/A$. Since the primary nucleons were bound together in a nucleus, and the cascade is very similar to one produced by A simultaneus proton cascades, each of energy E/A. Most of the primary cosmic ray nuclei split up near the top of the atmosphere into its constituents like nucleons. The primary cosmic ray flux $N_i(E)$ relates primary element flux $n_i(E)$ for each nuclei by

$$N_i(E)\,\mathrm{d}E = A_i\,n_i(E)\,\mathrm{d}E \tag{2}$$

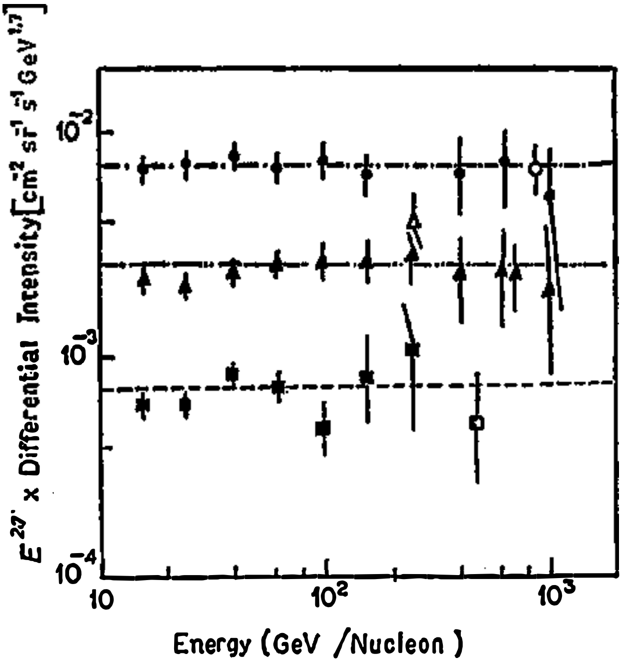

Fig. 2. Differential energy spectra for three groups of nuclei viz. medium M ($Z = 6$—9), heavy H ($Z = 10$—19) and very heavy VH ($Z \geq 20$):
Experimental data for M: ●-Simon et al.[5], ○-Abulova et al.[6]; H: ▲-Simon et al.[5], △-Abulova et al.[6]; VH: ■-Simon et al.[5]), □-Abulova et al.[6].
Fits to the data: —··—··—M, —·—·—H and — — — VH.

where A_i is the mass number of species i and n_i (E) is the differential energy spectrum of the species, expressed in units (m^2 s sr GeV/nucleon)$^{-1}$. The total nucleon flux at energy E (GeV/nucleon) has been estimated by

$$N(E)\,\mathrm{d}E = \sum_i N_i(E)\,\mathrm{d}E = \sum_i A_i K_i E^{-(\gamma_i+1)}. \quad (3)$$

The fluxes of nuclei at the same energy E (GeV/nucleus) may be obtained

$$N_{all}(E)\,\mathrm{d}E = \sum_{A_i} \text{nucleons}(A_i)\, A_i^{\gamma_i-1} = \sum_i A_i^{\gamma_i-1} N_i(E)\,\mathrm{d}E. \quad (4)$$

Fluxes of protons and neutrons created by the nuclei of mass numbers A_i and charge numbers Z_i can be estimated by multiplying Z_i/A_i and $(1 - Z_i/A_i)$ with $N_i(E)$.

4. *Results and discussion*

The fit to the integral proton and helium spectra in Fig. 1 follows the form

$$I_p(> E) = 1.03 \times E^{-1.7}\,(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1} \quad (5)$$

$$I_{He}(>E) = 0.057 \times E^{-1.7}\,(\mathrm{cm}^2\,\mathrm{s\,sr})^{-1}. \quad (6)$$

Full lines and broken lines in Fig. 1 are the fits to the *JACEE* data after relations (5) and (6).

TABLE 1

Element (i)	Mass number A_i	Differential spectral amplitudes K_i in per (cm^2 s sr GeV/nucleon)
p	1	1.7500
He	4	0.0969
Nuclei with		
$Z = 6$—9	16 (Average)	0.0072
$Z = 10$—19	26 (Average)	0.0026
$Z \geq 20$	56 (Average)	0.0007

Table shows the spectral amplitudes and mass numbers of different primary elemental fluxes for fixed spectral indices $\gamma_i = 1.7$.

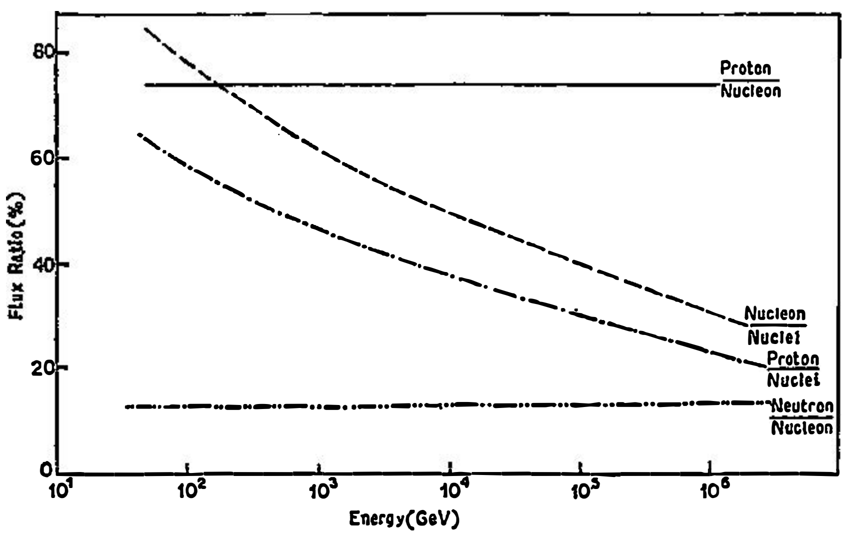

Fig. 3. Energy dependence of the conversion factors of different particles and nuclei: Factors at a particular energy E ———————— proton-nucleons, — — — — — nucleon-nuclei, —·—·—·—·— proton-nuclei, —··—··—··— neutron-nuclei.

The differential primary proton and different groups of nuclei spectra can be fitted by the power law fits of the form expressed in relation (1) and the estimated spectral amplitudes from Figs. 1 and 2 have been presented in Table 1 for fixed $\gamma_i = 1.7$ as functions of average mass numbers of nuclei. Using the spectral characteristics of different elemental fluxes in Table 1 and relation (3) the total primary nucleon spectrum has been estimated and found to follow the form

$$N_{nucleons}(E)\, dE = 2.36 \times 10^4\, E^{-2.7}\, dE\, (m^2 \text{ s sr GeV/nucleon})^{-1} \qquad (7)$$

in the spectral range $10^2 - 3 \times 10^5$ GeV. The only assumption made here is about the invariant nature of the spectral shapes of different primary cosmic ray nuclei up to 300 TeV energy.

The conversion factors for proton-nucleon, nucleon-nuclei, proton-nuclei and neutron-nucleon flux ratios have been plotted in Fig. 3. It is evident from Fig. 3. that proton-nucleon and neutron-nucleon flux ratios do not vary with energy. This fact supports the findings of Erlykin et al.[9]. The ratio of the fluxes of nucleon-nuclei and proton-nuclei at equal energy E may be denoted by the forms $1.24\,E^{-0.1}$ and $0.92\,E^{0.1}$ in the energy range $10^2 - 10^6$ GeV. The plot indicates that the proton component diminishes with energy and the nuclei intensity increases. The derived all particle spectrum has been estimated using relation (4) and parameters in Table 1 and follows the form

$$N_{all}(E)\,\mathrm{d}E = 1.9 \times 10^4\,E^{-2.6}\,\mathrm{d}E\,(\mathrm{m}^2\ \mathrm{s\ sr\ GeV/nucleus})^{-1} \tag{8}$$

in the spectral range $10^2 - 10^6$ GeV. The calculated primary spectrum has been plotted in Fig. 4 along with the satellite data of Grigorov et al.[2] and the Chacaltaya air shower data of La Pointe. Our calculated all particle spectrum from the recent measured spectra of protons and nuclei is in approximate agreement with the previous direct measurements[2,8].

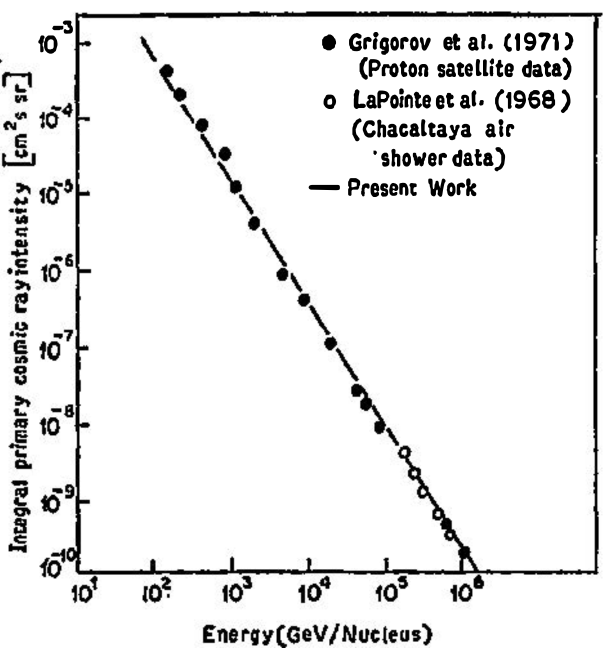

Fig. 4. Integral all particle primary spectrum:
● — proton satellite data of Grigorov et al.[2],
○ — Chacaltaya air shower data of La Pointe[8].
Full line is the present derived spectrum.

The conversion factors estimated from the present analysis can be used to calculate the elemental fluxes. Our results on the ratio of the fluxes of nuclei to protons and nuclei to nucleons of equal energy E may be denoted by the forms $1.0857\,E^{0.1}$ and $0.8051\,E^{0.1}$, respectively.

From the recent survey of Hillas[10] we have found that the total primary integral spectrum of Grigorov et al.[2] and La Pointe[8] can be fitted by a power law fit of the form

$$I_{all}(>E) = 1.4 \times E^{-1.65}\,(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1} \qquad (9)$$

in the spectral range $10^2 - 10^6$ GeV. The corresponding differential spectrum follows the form

$$N_{all}(E)\,\mathrm{d}E = 2.31 \times E^{-2.65}\,\mathrm{d}E\,(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV/nucleus})^{-1}. \qquad (10)$$

Using our derived conversion ratio for proton-nuclei we have calculated the primary proton spectrum from the Grigorov's differential all particle primary spectrum and the result follows the form

$$N_p(E)\,\mathrm{d}E = 2.13 \times E^{-2.75}\,\mathrm{d}E\,(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV/nucleon})^{-1}. \qquad (11)$$

The derived proton spectrum from the all particle spectrum of Grigorov et al.[2] is well in accord with the Goddard Space Flight Centre Group[3] proton spectrum. This fact supports the energy dependence of the conversion factors. Thus the conversion factor for proton-nuclei fluxes estimated from the present analysis corelates well between the all particle spectrum of Grigorov et al.[2] and Goddard Space Flight Centre Proton spectrum[3] favourably.

5. *Conclusion*

Using the recent proton and helium spectra of Japanese American Cooperative Emulsion Experiments and nuclei spectra from the compilation of Abulova et al. the primary nucleon and all particle spectra have been estimated using the superposition method. The derived spectra follow the forms:

$$N_{nucleon}(E)\,\mathrm{d}E = 2.36 \times 10^4\,E^{-2.7}\,\mathrm{d}E\,(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV/nucleon})^{-1}$$

and

$$N_{all\ particle}(E)\,\mathrm{d}E = 1.9 \times 10^4\,E^{-2.6}\,\mathrm{d}E\,(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV/nucleus})^{-1}.$$

The conversion factors for different primary particles and nuclei have been estimated viz., for proton-nucleon and neutron-nucleon flux ratios yield the values 0.74 and 0.13, respectively. On the other hand proton-nuclei and nucleon-nuclei at an equal energy E follow the forms $0.92\,E^{-0.1}$ and $1.24\,E^{-0.1}$, respectively.

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IZVOD PRIMARNOG SPEKTRA ČESTICA U KOZMIČKIM ZRAKAMA TE FAKTORI KONVERZIJE KOD SUPERVISOKIH ENERGIJA

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Primarni spektar svih čestica, te konverzioni faktori kozmičkog fluksa procijenjeni su na različitim energijama na osnovu direktnih mjerenja intenziteta protona i helija (Japanese American Cooperative Emulsion Experiments). Koristi se metoda superpozicije prilikom procjene fluksa nukleona iz spektra različitih jezgara.