Meson production and nuclear fragmentation of the nuclei in the atmosphere

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Propagation of primary and secondary cosmic rays in the atmosphere is calculated analytically. Two different cases of primary-cosmic-ray composition are used: the first case assumes a mixed composition of very heavy, heavy, middle, and α nuclei and nucleons; the second case considers only nucleons in the primary-cosmic-ray flux. The mechanism of multiple meson production is formulated according to the wounded-nucleon model for a nucleus-nucleus interaction and the scaling model for a nucleon-nucleon interaction. The mechanism of nuclear fragmentation is formulated according to experimental values of the fragmentation parameters at low energy. The calculated results of the electromagnetic flux are compared with the results of mountain experiments with a large-scale emulsion chamber and experimental data at airplane altitudes. From these comparisons the model with heavy nuclei gives the best fit.

I. INTRODUCTION

The diffusion equation in the atmosphere for nuclear active cosmic particles and an electromagnetic component has been studied by several authors[1-3] using several models of nuclear interactions and a primary-cosmic-ray flux dominated by nucleons. However, simulation calculations[4,5] of several authors, using a nuclear interaction model with a scaling property and a proton dominant primary-cosmic-ray flux, give a significantly larger frequency of electromagnetic families than observed. There are various possibilities for explaining this discrepancy: namely, (a) heavy nuclei in the primary flux, or (b) a strong change in the mechanism of multiple meson production at very high energies.

In this paper two different cases of primary-cosmic-ray composition are used to study the development of the electromagnetic components in the atmosphere. The first case assumes a mixed composition of very heavy, heavy, middle, and α nuclei and nucleons, and the second case considers only nucleons in the primary-cosmic-ray flux.

II. ATTENUATION OF COSMIC-RAY HEAVY-NUCLEI FLUXES IN THE ATMOSPHERE BY FRAGMENTATION

The energy region of cosmic-ray fluxes observed in mountain experiments with large emulsion chambers is beyond the TeV region.

The groups of cosmic-ray nuclear component in the upper atmosphere can be represented by the following scheme:

Group	Atomic weight
VH (very heavy)	$A \geq 39$
H (heavy)	$32 \leq A \leq 20$
M (medium)	$16 \leq A \leq 12$
α	$A=4$
n (nucleons)	$A=1$

The genetic relation for fragmentation process of the cosmic-ray nuclear components when they propagate in the atmosphere is represented in Fig. 1.

The chemical composition and energy spectra of primary cosmic rays in GeV-TeV region has been measured in the experiments with airborne balloon emulsion chamber[6] and experimental data of air shower compared with Monte Carlo simulation. The relative abundances in the ~ 25 GeV/nucleon region have been determined by Goodman *et al.*,[7] and in the TeV/nucleon region no significant change in chemical composition of primary cosmic rays is observed. The results of the so-called normal composition have been compiled by Nikolsky;[8] Table I summarizes the results at the energy of $\gtrsim 0.1$ TeV/nucleon.

The propagation of heavy nuclei in the atmosphere is calculated assuming the following.

(a) The angular distribution of the fragmentation products is irrelevant (one-dimensional model).

(b) At high energies ($E > 10^{12}$ eV) the energy loss by ionization may be neglected.

(c) The fragments produced in interactions preserve the energy per nucleon of the incident nucleus.

The diffusion equation of the heavy nuclei of the

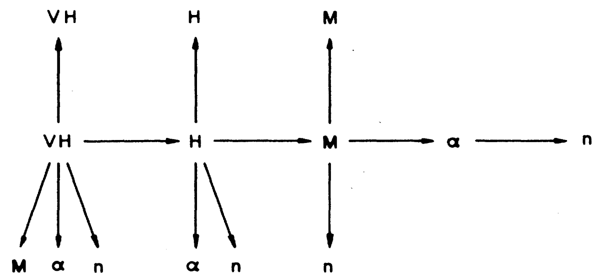

FIG. 1. Genetic relation for fragmentation process of the cosmic-ray nuclei in the atmosphere.

charge group is

$$\frac{dN_j(E,X)}{dx} = -\frac{N_j(E,X)}{\lambda_j(E)} + \sum_{i>j} \frac{P_{ij}(E)N_i(E,X)}{\lambda_i(E)} , \quad (1)$$

where $N_j(E,X)$ is the number of nuclei of type j with energy E at X and $X+dX$ atmospheric depth; λ_j is the breakup collision mean free path of the nuclei of type j and P_{ij} is the fragmentation probability from charge group i to charge group j. Then the solution of this equation is obtained[9] for P_{ij} and λ_i independent of the energy as

$$N_j(E,X) = N_j(0,E)e^{-x/\Lambda_j} + \sum_{i>j} K_{ij}(e^{-x/\Lambda_j} - e^{-x/\Lambda_i}) , \quad (2)$$

where $j=1,2,3,4,5$: $j=1$ for nucleons, $j=2$ for alpha particles, $j=3$ for middle nuclei, $j=4$ for heavy nuclei, and $j=5$ for very heavy nuclei, and

$$K_{ij} = \alpha_{ij} \left[\frac{P_{ij}}{\lambda_i} N_i(E,0) - \sum_{l=j+1}^{i-1} \frac{P_{lj}}{\lambda_j} K_{li} + \sum_{l=i+1}^{5} \frac{P_{ij}}{\lambda_i} K_{li} \right] , \quad (3)$$

$$\Lambda_j = \frac{\lambda_j}{1-P_{jj}} , \quad \alpha_{ij} = \frac{\Lambda_i \Lambda_j}{\Lambda_j - \Lambda_i} . \quad (4)$$

Figure 2 shows the attenuation of cosmic nuclei fluxes in the atmosphere by the fragmentation process, according to (2). We have used the experimental values of the fragmentation parameters P_{ij} given by Allkofer and Heinrich[9] and Saito.[10]

TABLE I. Summary of results at the energy of ≳0.1 TeV/nucleon.

Group	Notation	Intensity of particles $E \geq 0.1$ TeV/nucleon ($m^{-2}s^{-1}sr^{-1}$)
$A=1$	n	3.3±0.2
$A=4$	α	0.12±0.02
$12 \leq A \leq 16$	M	0.018±0.0023
$20 \leq A \leq 32$	H	0.0056±0.001
$39 \leq A \leq 56$	VH	0.0014±0.0003

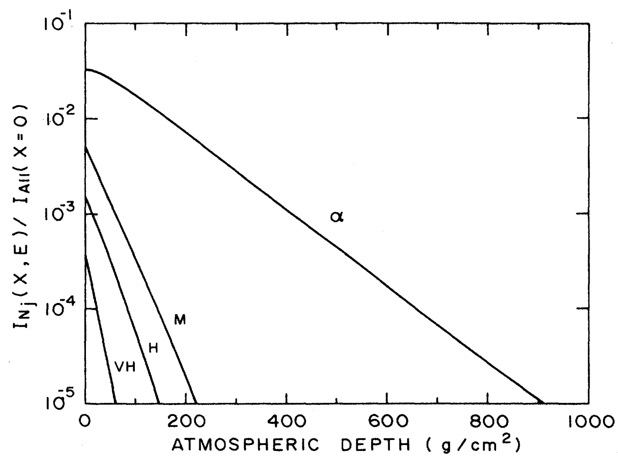

FIG. 2. Attenuation of cosmic nuclei fluxes normalized by integrating all flux in the atmosphere by fragmentation for VH (very heavy nuclei), H (heavy nuclei), M (medium nuclei), and α.

III. MESON PRODUCTION

In the present paper we use the wounded-nucleon model[11,5] for nucleus-nucleus interactions. In this model the mean number of charged pions produced in nucleus-nucleus interactions is

$$\langle n_\pi \rangle_{A,B} = \tfrac{1}{2} \langle n_\pi \rangle_{pp} W_{AB} , \quad (5)$$

where A and B are the atomic weights of the projectile and the target nucleus. $\langle n_\pi \rangle_{pp}$ is the mean number of charged pions per pp collision. $\frac{1}{2}$ in this relation is due to the fact that each nucleon-nucleon interaction requires two wounded nucleons. The number of wounded nucleons, W_{AB}, is defined to be the number of nucleons that have interacted at least once:

$$W_{AB} = \frac{A\sigma_{PB}}{\sigma_{AB}} + \frac{B\sigma_{PA}}{\sigma_{AB}} ; \quad (6)$$

here σ_{PB} and σ_{PA} are the nucleon-nucleus inelastic cross sections and σ_{AB} is the nucleus-nucleus cross section:

$$\sigma_{AB} = \pi(R_A + R_B - b)^2 , \quad (7)$$

where

$$R_A = r_0 A^{1/3}, \quad R_B = r_0 B^{1/3}, \quad r_0 = 1.29 \text{ fm} ,$$

and b is a transparency constant:

$$b = 1.189 \exp[-0.0545 \min(A,B)] .$$

For the cosmic-ray nucleus interaction in the atmosphere W_{AB} was determined by several authors[5] and various models. The mechanism of multiple meson production is formulated according to the scaling model for nucleon-nucleon interaction.

IV. π-MESON FLUX

The diffusion equation of pions in the atmosphere is given as

$$\frac{\partial \pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi(E)} + \int_E^\infty \frac{dE'}{E} \frac{\pi(E',X)F_{\pi\pi}(E,E')}{\lambda_\pi(E')} + \sum_j \int_E^\infty \frac{dE'}{E} \frac{N_j(E',X)F_{N_j\pi}(E',E)}{\lambda_j(E')} , \quad (8)$$

where $\pi(E,X)$ is the number of pions with energy E at X and $X+dX$ atmospheric depth, λ_π and λ_j are the collision mean free paths of the pions and nucleus, respectively, $F_{\pi\pi}(E',E)$ and $F_{N_j\pi}(E',E)$ are the production energy spectra of pions through pion-nucleus and nucleus-nucleus collisions, respectively, and $N_j(E',X)$ is the solution of the diffusion equation (2) for nuclei.

According to conventional hadronic "scaling,"

$$F_{\pi\pi}(E,E') \rightarrow F_{\pi\pi}(E/E') , \quad F_{N_j\pi}(E,E') \rightarrow F_{N_j\pi}(E/E') \quad (9)$$

and we can introduce

$$\pi(X,E/\eta) = \pi(E,X)\eta^{\gamma+1} , \quad N_j(X,E/\eta) = N_j(E,X)\eta^{\gamma+1} , \quad (10)$$

where $\eta = E/E'$. Let us assume that the energy spectrum of primary cosmic rays is a power function with exponent $\gamma+1$ and the diffusion equation for pions is

$$\frac{\partial \pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi} + \frac{\pi(E,X)}{\lambda_\pi}\int_0^1 \eta^{\gamma-1} F_{\pi\pi}(\eta)d\eta + \sum_j \frac{N_j(E,X)}{\lambda_j}\int_0^1 \eta^{\gamma-1}F_{N_j\pi}(\eta)d\eta . \quad (11)$$

Now we introduce the relations

$$Z_{\pi\pi} = \int_0^1 \eta^{\gamma-1}F_{\pi\pi}(\eta)d\eta , \quad Z_{N_j\pi} = \int_0^1 \eta^{\gamma-1}F_{N_j\pi}(\eta)d\eta \quad (12)$$

and the diffusion equation of pions is given by

$$\frac{\partial \pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi} + \frac{\pi(E,X)}{\lambda_\pi}Z_{\pi\pi} + \sum \frac{N_j(E,X)}{\lambda_j}Z_{N_j\pi} . \quad (13)$$

The solution of this equation is

$$\pi(E,X) = \sum_j E_{N_j}^{-(\gamma+1)} \frac{Z_{N_j\pi}}{\lambda_j}\left[N_j(0)\left[\frac{e^{-x/\Lambda_j}-e^{-x/\Lambda_\pi}}{1/\Lambda_\pi - 1/\Lambda_j}\right] + \sum_{i>j} K_{ij}\left[\frac{e^{-x/\Lambda_j}-e^{-x/\Lambda_\pi}}{1/\Lambda_\pi - 1/\Lambda_j} - \frac{e^{-x/\Lambda_i}-e^{-x/\Lambda_\pi}}{1/\Lambda_\pi - 1/\Lambda_i}\right]\right] , \quad (14)$$

where $\Lambda_\pi = \lambda_\pi/(1-Z_{\pi\pi})$.

The accelerator data[12] for $Z_{\pi\pi}$ and $Z_{n\pi}$ (where n is nucleon) give $Z_{\pi\pi} \approx 0.28$ and $Z_{n\pi} \approx 0.081$ for $\gamma = 1.71$. For nucleus-nucleus collisions with multiple production of pions we have

$$Z_{N_j\pi} \approx Z_n W_A , \quad (15)$$

where W_A is the wounded nucleon in the projectile nucleus.

Figure 3 shows the longitudinal development of pions in the atmosphere; the dashed curve is calculated with a mixed composition in the primary flux (very heavy, heavy, middle, α, and nucleon) and the solid curve is calculated with only the nucleon in the primary flux.

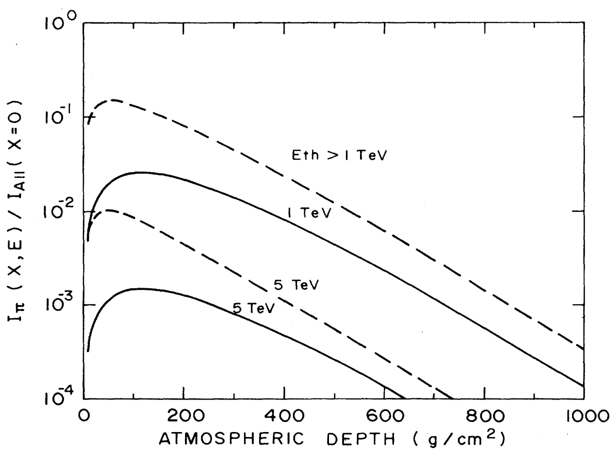

FIG. 3. Longitudinal development of pions normalized by integrating all flux in the atmosphere. Dashed curves: calculated with mixed composition in the primary flux. Solid curves: calculated with only nucleons in the primary flux.

V. ELECTROMAGNETIC COMPONENT

The flux of the electromagnetic component in the atmosphere is obtained from the production spectrum of neutral pions which in turn comes from the charged-pion production spectrum, assuming the π^0 meson decays into two γ rays with quite a short lifetime ($\sim 10^{-16}$ s) and charge independent of meson production. The resultant γ ray produces successive electromagnetic components by the cascade process.

The γ-ray production spectrum[2] is given by

$$P_\gamma(E,X) = 2\int_E^\infty \frac{dE'}{E'}\frac{1}{2}P_{\pi^\pm}(E',X) , \quad (16)$$

where $P_{\pi^\pm}(E,X)$ is the production spectrum of the charged pions:

$$P_{\pi^\pm}(X,E) = \frac{\pi(X,E)}{\lambda_\pi}Z_{\pi\pi} + \sum_j \frac{N_j(x,E)}{\lambda_j}Z_{N_j\pi} . \quad (17)$$

Thus the γ-ray production spectrum is given by

$$P_\gamma(E,X) = \frac{Z_{\pi\pi}}{\lambda_\pi}\int_E^\infty \frac{\pi(E',X)}{E'}dE' + \sum_j \frac{Z_{N_j\pi}}{\lambda_j}\int_E^\infty \frac{N_j(E',X)}{E'}dE' . \quad (18)$$

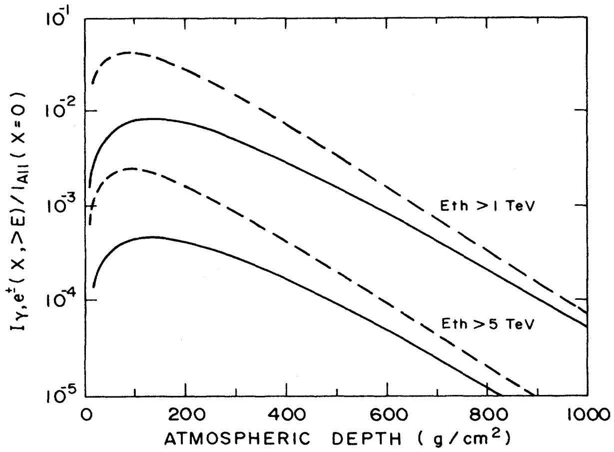

FIG. 4. Longitudinal development of electromagnetic component normalized by integrating all flux in the atmosphere. Dashed curves: calculated with mixed composition in the primary flux. Solid curves: calculated with only nucleons in the primary flux.

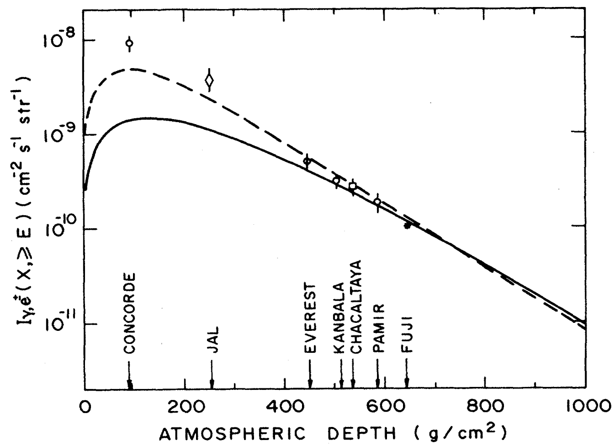

FIG. 5. Altitude variation of integral electromagnetic flux; the analytical calculation has been done for pure nucleon primary flux (solid curve) and mixed composition in the primary flux (dashed curve). The experimental results are summarized in Ref. 16.

The electromagnetic component by the cascade process produced by an incident photon of primary energy E is given by the one-dimensional cascade theory of approximation A as

$$(e+\gamma)(E_0,E,X) = \frac{1}{2\pi i}\int du \left[\frac{E_0}{E}\right]^u \frac{1}{E}[N_1(u)e^{\lambda_1(u)x/X_0} + N_2(u)e^{\lambda_2(u)X/X_0}] , \quad (19)$$

where $N_1(u)$, $N_2(u)$, $\lambda_1(u)$, $\lambda_2(u)$, X_0 are parameters familiar in cascade theory.[13]

Further, the differential electromagnetic flux is

$$F_\gamma(X,E) = \int_0^x dt \int_{E'}^{\infty} dE_\gamma P_\gamma(E_\gamma,t)(e+\gamma)(E_\gamma,E,X-t) ; \quad (20)$$

in the integral form it becomes

$$I_\gamma(E,X) = \int_E^\infty F_\gamma(E',X)dE' . \quad (21)$$

Figure 4 shows the longitudinal development of the electromagnetic component normalized by integrating all fluxes in the atmosphere. The broken curves are calculated with a mixed composition in the primary flux and the solid curves correspond to a primary flux with only nucleons.

VI. COMPARISON WITH EXPERIMENTAL RESULTS

Our analytical result of the longitudinal development of the electromagnetic component (γ ray and electron positron) is compared with the result of mountain experiments with large-scale emulsion chambers at Pamir, Mt. Fuji, Chacaltaya,[14,15] Kanbala, Everest, and on-board airplane data. The experimental results have been compiled by Capdevielle *et al.*[16]

Two different analytic results are found in this paper according to the cases of primary-cosmic-ray flux composition: Figure 5 shows the longitudinal development of the electromagnetic component, the analytical calculation has been done for pure nucleon primary flux (solid curve), and mixed composition in the primary flux (broken curve). Both are compared with experimental values of electromagnetic flux.

VII. CONCLUSION

Our calculation of the electromagnetic flux development in the atmosphere considers the dependence on the composition of the primary flux. The effect of including heavy nuclei (especially pion production by interactions of heavy nuclei) is to increase the electromagnetic flux at airplane altitudes in a way that resembles the data.

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