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MESON PRODUCTION AND NUCLEAR FRAGMENTATION OF NUCLEUS IN THE ATMOSPHERE

by

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ABSTRACT

Propagation of the primary and secondary cosmic ray in the atmosphere is calculated analitically. Two different cases of primary cosmic ray composition are used; the first case concerns the mixed composition of very heavy, heavy, middle, light nuclei and nucleons; and 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 nucleus-nucleus interaction and the scaling model for nucleon-nucleon interaction. The mechanism of nuclei fragmentation is formulated according to the 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 large scale emulsion chamber and experimental data at airplane altitude. From these comparisons the calculation of electromagnetic flux altitude variation of the first case gives the best fit with experimental data than the second case.

Key-words: Meson production; Nuclear fragmentation in atmosphere; Diffusion equation.

1 INTRODUCTION

The diffusion equation in the atmosphere for nuclear active cosmic particles and electromagnetic component has been studied by several authors (Pal and Peters[1] 1969; Ohsawa[3] 1971; Oliveira Castro[4] 1977) according to several models of nuclear interactions and nucleon dominant particle in the primary cosmic ray flux.

However, simulation calculations[5,6] of several authors using nuclear model with scaling property and proton dominant particle in the primary cosmic ray flux, always give a significantly larger frequency of electromagnetic families than the observed. There are various possibilities for explaining this discrepancy like:

a) Heavy nucleus in the primary flux
b) 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 for study of meson and electromagnetic component development in the atmosphere. The first case concerns the mixed composition of very heavy, heavy, middle, light nuclei and nucleons, and the second case considers only nucleons in the primary cosmic ray flux.

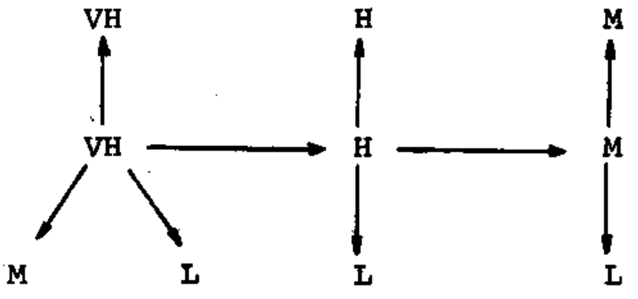
2 ATTENUATION OF COSMIC RAY HEAVY NUCLEI FLUXES IN THE ATMOSPHERE BY FRAGMENTATION

The energy region of cosmic ray fluxes observed in mountain experiments with large emulsion chamber is beyound TeV regions.

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

GROUP	VH very heavy	H heavy	M middle	L light	n nucleons
Atomic number	$Z \geq 20$	$10 \leq Z \leq 19$	$6 \leq Z \leq 9$	$2 \leq Z \leq 5$	$Z=1$ $Z=0$

The genetic relation for fragmentation process of the cosmic ray nuclear components when they propagate in the atmosphere can be represented by



The chemical composition and energy spectra of primary cosmic ray in the region of GeV-TeV is measured in the experiments with air borne balloon emulsion chamber[1]. The relative abundances (in TeV region for nucleo) of the primary heavy nucleus group and nucelons can be written as:

All: n : L : M : H : VH $\simeq$ 1 : 0,63 : 0,02 : 0,16 : 0.01 : 0.06

The propagation of heavy nuclei in the atmosphere is calculated assuming:

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

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

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

The diffusion equation of heavy nuclei of the charge group j is:

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

where $N_j(E,X)$ is the number of nucleus of type j with energy E at X and X + dX atmospheric depth; λ_j is the breakup collision mean free path of 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[7] for P_{ij} and λ_i independent of the energy as:

$$N_j(E,X) = N_j(O,E)e^{-x/\Lambda_j} + \sum K_{ij}(e^{-x/\Lambda_j} - e^{-x/\Lambda_i}) \tag{2}$$

Where

$$K_{ij} = \alpha_{ij}\left(\frac{P_{ij}}{\lambda_i} N_i(E,0) + \sum_{\ell} \frac{P_{\ell i}}{\lambda_\ell} K_{\ell i} + \sum_{\ell} \frac{P_{ij}}{\lambda_i} K_{i\ell}\right)$$

$$\Lambda_j = \frac{\lambda_j}{1 - P_{jj}} \qquad \alpha_{ij} = \frac{\Lambda_i \Lambda_j}{\Lambda_j - \Lambda_i}$$

Fig. 1 shows the attenuation of cosmic nuclei fluxes in the atmosphere by fragmentation process, according to (2). We have used the experimental values of fragmentation parameters P_{ij} given by Allkofer and Heinrick[7], Saito[8].

3 MESON PRODUCTION

In the present paper we use the wounded nucleon model[9,6] for nucleus-nucleus interaction. In this model the mean number of charged pions produced in nucleus-nucleus interaction is

$$\langle n_\pi \rangle_{A,B} = \frac{1}{2} \langle n_\pi \rangle_{pp} W_{AB}$$

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

$$W_{AB} = \frac{A\sigma_{PB}}{\sigma_{AB}} + \frac{B\sigma_{PA}}{\sigma_{AB}}$$

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

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

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

b is a transparency constant

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

For cosmic ray nucleus interaction in the atmosphere W_{AB} was determined by several authors[6] and models. The mechanism of multiple meson production is formulated according to the scaling model for nucleon-nucleon interaction.

4 π-MESON FLUX

The diffusion equation of pions in the atmosphere is given as follows:

$$\frac{\partial\pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi(E)} + \int_E^\infty \frac{dE'}{E}\,\frac{n(E',X)F_{n\pi}(E,E')}{\lambda_n(E')}$$

$$+\int_B^\infty \frac{dE'}{E}\,\frac{\pi(E',X)F_{\pi\pi}(E,E')}{\lambda_\pi(E')} + \sum_j \int_E^\infty \frac{dE'}{E}\,\frac{N_j(E',X)F_{N_j\pi}(E',E)}{\lambda_{N_j}(E')}$$

Where $\pi(E,X)$ is the number of pions with energy E at X and X + dX atmospheric depth, λ_π, λ_n and λ_{N_j} are the collision mean free path of pions, nucleons and nucleus respectively; $F_{n\pi}(E',E)$, $F_{\pi\pi}(E',E)$ and $F_{N_j\pi}(E',E)$ are the production energy spectra of pions through nucleon-nucleus, pion-nucleus and nucleus-nucleus collision respectively.

The last term is the contribution of nucleus (VH,H,M,L) at meson flux and $N_j(E',X)$ is the solution of the diffusion equation of nucleus found in 2.

According to hadronic conventional "Scaling"

$$F_{n\pi}(E,E') \rightarrow F_{n\pi}(E/E')$$

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

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

and we can introduce

$$n(X,E/\eta) = n(E,X)\eta^{\gamma+1}$$

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

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

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

$$\frac{\partial\pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi} + \frac{n(E,X)}{\lambda_n}\int_0^1 \eta^\gamma F_{n\pi}(\eta)\,d\eta$$

$$+\frac{\pi(E,X)}{\lambda_\pi}\int_0^1 \eta^\gamma F_{\pi\pi}(\eta)\,d\eta + \sum_j \frac{N_j(E,X)}{\lambda_{N_j}}\int_0^1 \eta^\gamma F_{N_j\pi}(\eta)\,d\eta$$

now we introduce the relations

$$Z_{n\pi} = \int_0^1 \eta^\gamma F_{n\pi}(\eta)\,d\eta$$

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

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

and the diffusion equation of pions is given by:

$$\frac{\partial\pi(E,X)}{\partial X} = -\frac{\pi(E,X)}{\lambda_\pi} + \frac{n(E,X)}{\lambda_n} Z_{n\pi} + \frac{\pi(E,X)}{\lambda_\pi} Z_{\pi\pi} + \sum \frac{N_j(E,X)}{\lambda_{N_j}} Z_{N_j\pi}$$

the solution of this equation is

$$\pi(E,X) = n_o E^{-(\gamma+1)}\,\frac{Z_{n\pi}}{\lambda_n}\left(\frac{e^{-x/\Lambda_n} - e^{-x/\Lambda_\pi}}{1/\Lambda_\pi - 1/\Lambda_n}\right) +$$

$$+\sum_j E_{N_j}^{-(\gamma+1)}\,\frac{Z_{N_j\pi}}{\lambda_{N_j}}\left[N_j(0)\left(\frac{e^{-x/\Lambda_{N_j}} - e^{-x/\Lambda_\pi}}{\frac{1}{\Lambda_\pi} - \frac{1}{\Lambda_{N_j}}}\right) + \sum_{i>j} K_{ij}\left(\frac{e^{-x/\Lambda_{N_j}} - e^{-x/\Lambda_\pi}}{\frac{1}{\Lambda_\pi} - \frac{1}{\lambda_{N_j}}} -\right.\right.$$

$$\left.\left. - \frac{e^{-x/\Lambda N_i} - e^{-x/\Lambda_\pi}}{\frac{1}{\Lambda_\pi} - \frac{1}{\Lambda_{N_j}}}\right)\right]$$

Where $\Lambda_\pi = \frac{\Lambda_\pi}{1 - Z_{\pi\pi}}$.

The last term is the contribution of primary heavy nucleus to pions component.

The accelerator data[10] for $Z_{\pi\pi}$ and $Z_{n\pi}$ (where n is nucleon) gives $Z_{\pi\pi} \simeq 0.28$ and $Z_{n\pi} \simeq 0.081$ for $\gamma = 1.71$. For nucleus nucleus collisions with multiple production of pions we have:

$$Z_{N_j\pi} \simeq Z_{n\pi} W_{AB}$$

Fig. 2 shows the longitudinal development of pions in the atmosphere, broken curve is calculated with mixed composition in the primary flux (very heavy, heavy, middle, little and nucleon) and solid curve is calculated with only nucleon in the primary flux.

5 ELECTROMAGNETIC COMPONENT

The flux of the electromagnetic component in the atmosphere can be obtain from the production spectrum of neutral pions which comes from the charged pions spectrum under the assumption of π^0 meson decays in two γ-rays with quite a short lifetime $(\sim 10^{-16}\text{S})$ and charge independence of meson production. The resultant γ-ray produces successive electromagnetic components by the cascade process.

The production spectrum of γ-ray[3] is given by

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

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

$$P_{\pi^\pm}(E,X) = \int_0^1 \frac{n(X,E/\eta)F_{n\pi}(x)}{\lambda_n}\frac{d\eta}{\eta} + \int_0^1 \frac{\pi(X,E/\eta)F_{\pi\pi}(\eta)d\eta}{\lambda_\pi \qquad \eta}$$

$$+ \sum_j \int_0^1 \frac{N_j(X,E/\eta)F_{N_j\pi}(\eta)}{\lambda_{N_j}}\frac{d\eta}{\eta}$$

or

$$P_{\pi^\pm}(E,X) = \frac{n(E,X)}{\lambda_n} Z_{n\pi} + \frac{\pi(E,X)}{\lambda_\pi} Z_{\pi\pi} + \sum_j N_j(E,X) Z_{N_j}$$

With

$$Z_{ab} = \int_0^1 F_{ab}(\eta)\eta^\gamma d\eta$$

and the production spectrum of gamma ray is given by

$$P_\gamma(E,X) = \frac{Z_{n\pi}}{\lambda_n}\int_E^\infty \frac{n(E,X)}{E'}dE' + \frac{Z_{\pi\pi}}{\lambda_\pi}\int_E^\infty \frac{\pi(E',X)}{E'}dE' +$$

$$+ \sum_j \frac{Z_{N_j\pi}}{\lambda_{N_j}}\int_E^\infty \frac{N_j(E',X)}{E'}dE'$$

The last term is the contribution of heavy nucleus to gamma ray component.

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

$$(e+\gamma)(E_o,E,X) = \frac{1}{2\pi i}\int du\left(\frac{E_o}{E}\right)^{u}\frac{1}{E}\left(N_1(u)e^{\frac{\lambda_1(u)x}{X_o}} + N_2(u)e^{\frac{\lambda_2(u)X}{X_o}}\right)$$

Where $N_1(u)$, $N_2(u)$, $\lambda_1(4)$, $\lambda_2(u)$, X_o are parameters familiar in cascade theory.

Further, the differential electromagnetic flux is

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

in the integral form it becomes

$$I_\gamma(E,X) = \int_E^{\infty} F_\gamma(E',X)\,dE'$$

Fig. 3 shows the longitudinal development of electromagnetic component normalized by integrating all fluxos in the atmosphere. The broken curves are calculated with mixed composition in the primary flux and the solid curves corresponds to primary flux with only nucleons.

6 COMPARISON WITH EXPERIMENTAL RESULTS

Our analytical result of the longitudinal development of electromagnetic component (gamma-ray and electron-positron) is compared with the results of mountain experiments with large scale emulsion chamber at Pamir, Mt. Fuji, Chacaltaya,[11,12], Kanbala, Everest and on-board aiplane data. The experimental results have been compiled by J.N. Capdeviele et al.[13].

Two different analytic results are found in this paper according to the two cases of primary cosmic ray flux composition. Fig. 4 shows the longitudinal development of electromagnetic component normalized by integrating all fluxes in the atmosphere. The broken curve is calculated with mixed composition in the primary flux and the solid curve corresponds to primary flux with only nucleons, for detection energy larger than 3 TeV and the exponent of the power function of the energy spectrum is the same of the exponent of the primary energy spectrum. This figure shows the difference of the vertical electromagnetic flux in the atmosphere depending on the cases choisen. However this difference decreases when the atmospheric depth rises.

On the other hand if the power exponent of the energy spectrum is also adapted at the best experimental value of $\gamma = 2$ this difference decreases especially for $X > 500 g/cm^2$ as shown in Fig. 5 where our analytical result is compared with experimental values of electromagnetic flux.

The value of the primary flux in the top of the atmosphere is determined from this comparison which gives the best fit value of primary flux be $3.3\ 10^{-6} (cm^{-2}\ Sec^{-1}\ Str^{-1})$ for energy larger than 5 TeV/nucleus.

7 CONCLUSION

Our analytical calculations of electromagnetic flux development in the atmosphere are different depending on the composition of the primary flux, this difference decreases when the atmospheric depth rises. This is in agreement with the rapid decrease of flux of heavy primaries for fragmentation process. The contribution of heavy primaries to meson flux and consequently to electromagnetic component for low atmospheric depth is larger than the contribution at high atmospheric depth. This is because the multiplicity of mesons in nucleus-nucleus interaction is greater than the multiplicity of mesons in nucleon-nucleus interaction.

We see that in our Fig. 5 the mixed primary flux case gives a better fit, although above mountain altitude this is not conclusive because of the poor statistics of experimental data in this region. From mountain altitudes and below both cases agree.

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FIGURE CAPTION

Fig. 1 - Attenuation of Cosmic Nuclei fluxes normalized by integral all flux in the atmosphere by fragmentation

VH - very heavy nucleus

H - heavy nucleus

M - middle nucleus

L - light nucleus

In this figure the atomic number for light nucleuns is $3 \leq Z \leq 5$.

Fig. 2 - Longitudinal development of pions normalized by integral all flux in the atmosphere.

broken curves - Calculated with mixed composition in the primary flux.

solid curves - Calculated with only nucleons in the primary flux.

Fig. 3 - Longitudinal development of electromagnetic component normalized by integral all flux in the atmosphere.

broken curves - Calculated with mixed composition in the primary flux.

solid curves - Calculated with only nucleons in the primary flux.

Fig. 4 - Longitudinal development of electromagnetic component normalized by integral all flux. The broken curve is calculated with mixed composition in the primary flux and the solid curve corresponds to primary flux with only nucleons, for detection energy larger than 3 TeV and the exponent of the power function of the energy

spectrum is the same of the exponent of the primary spectrum.

Fig. 5 - Altitude variation of integral electromagnetic flux, the broken curve is calculated with mixed composition in the primary flux and the solid curve correspond to primary flux with only nucleons, for detection energy large than 5 TeV and the power exponent of the energy spectrum is adapted at the best experimental value of $\gamma = 2$.

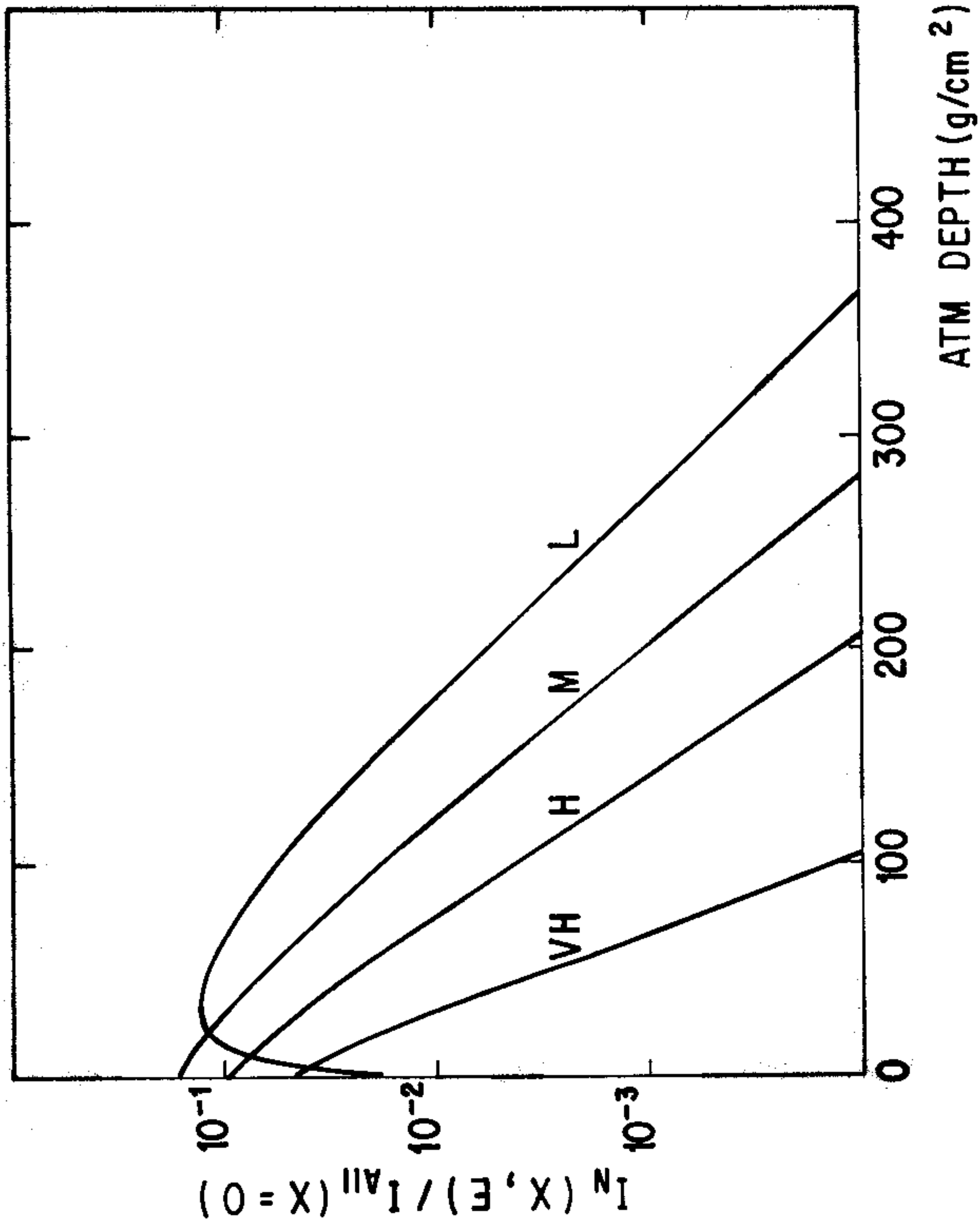

FIG.1

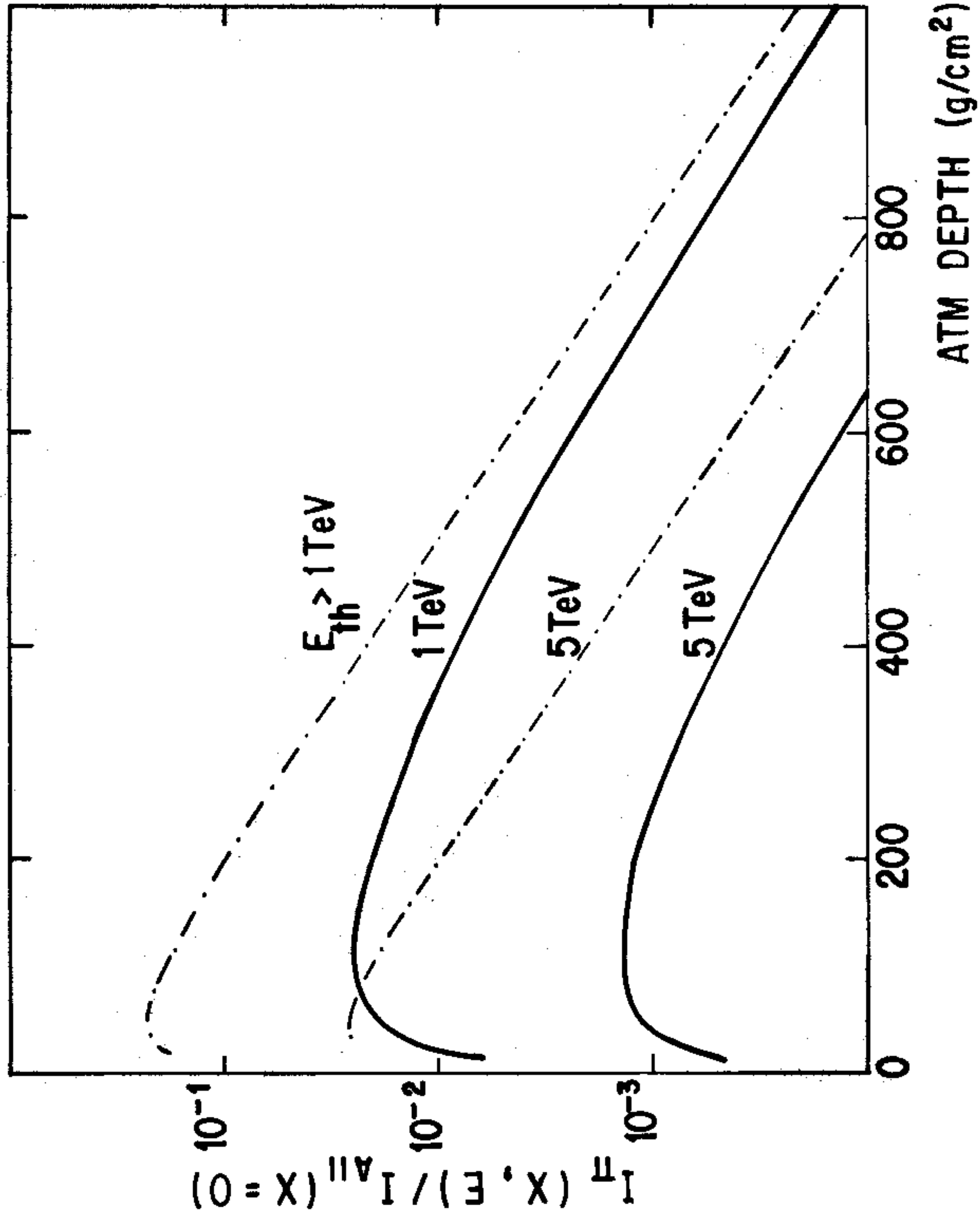
$I_\pi\ (X,\ E)\ /\ I_{All}\ (X = 0)$
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
ATM DEPTH (g/cm^2)
$E_{th} > 1$ TeV
1 TeV
5 TeV
5 TeV

FIG. 2

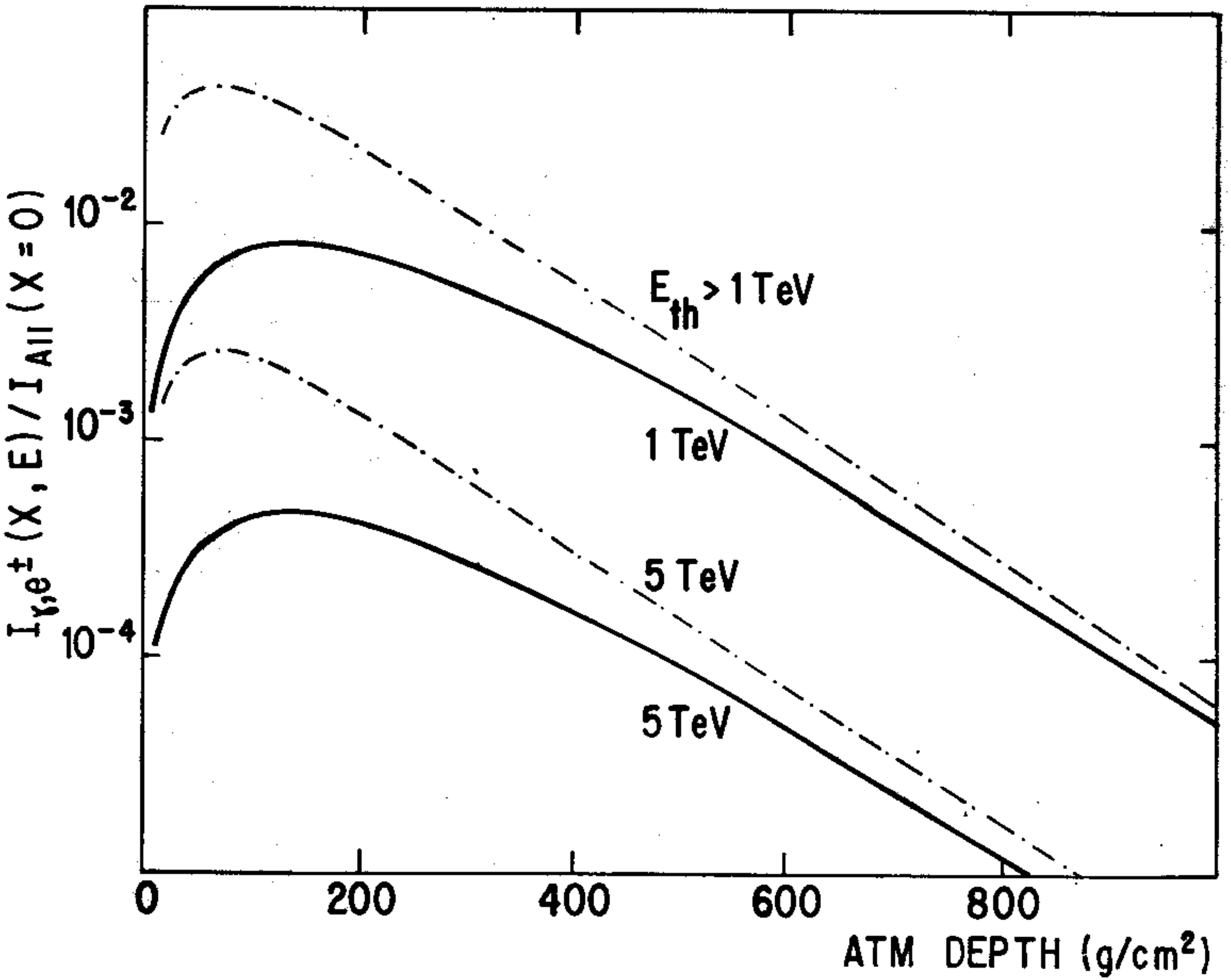
$I_{\gamma,e^{\pm}}(X, E)/I_{All}(X=0)$
10^{-2}
10^{-3}
10^{-4}
$E_{th} > 1$ TeV
1 TeV
5 TeV
5 TeV
0
200
400
600
800
ATM DEPTH (g/cm^2)

FIG.3

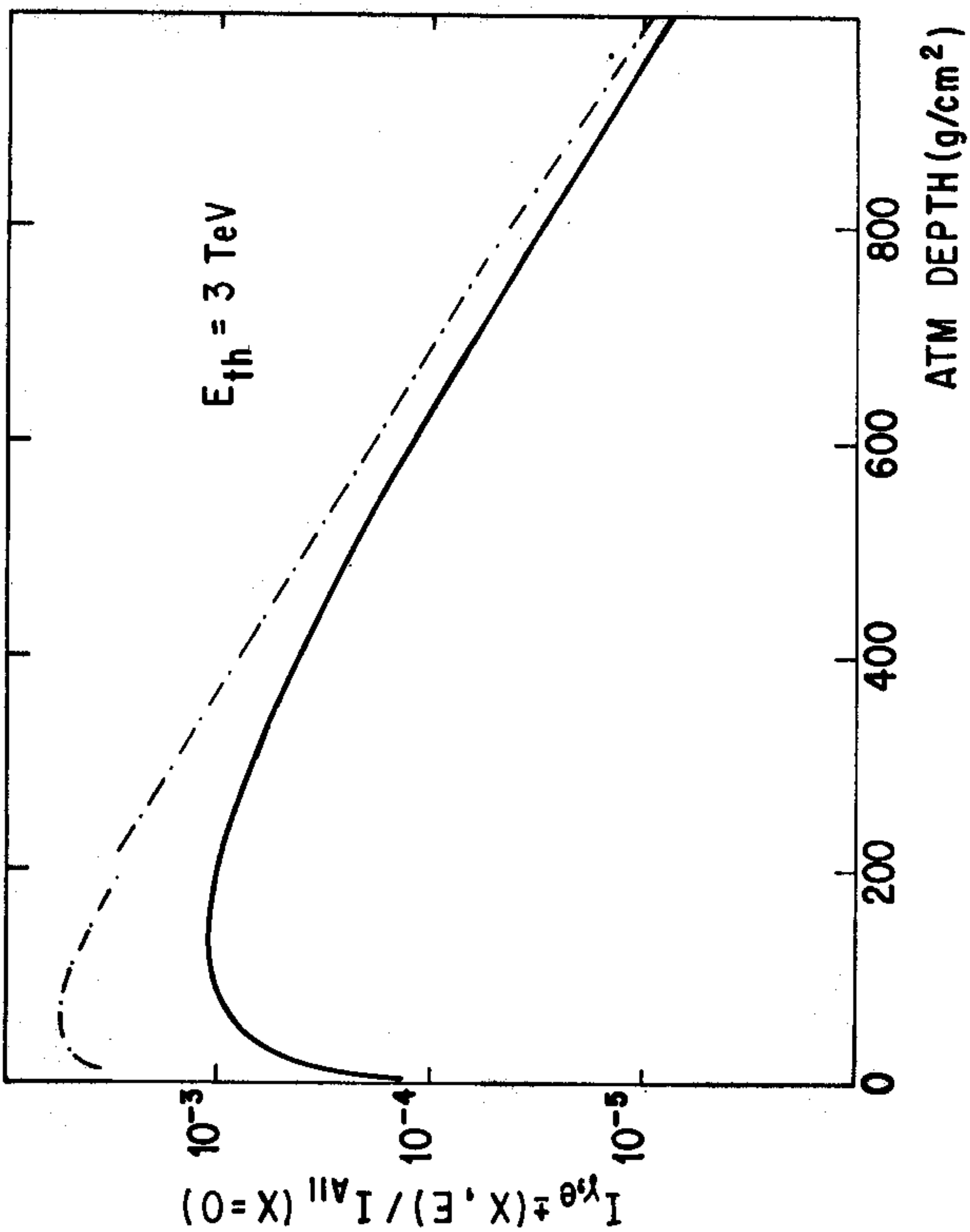
E_th = 3 TeV
ATM DEPTH (g/cm²)
0
200
400
600
800
10⁻³
10⁻⁴
10⁻⁵
I γ,θ ±(X , E) / I All (X = 0)

FIG.4

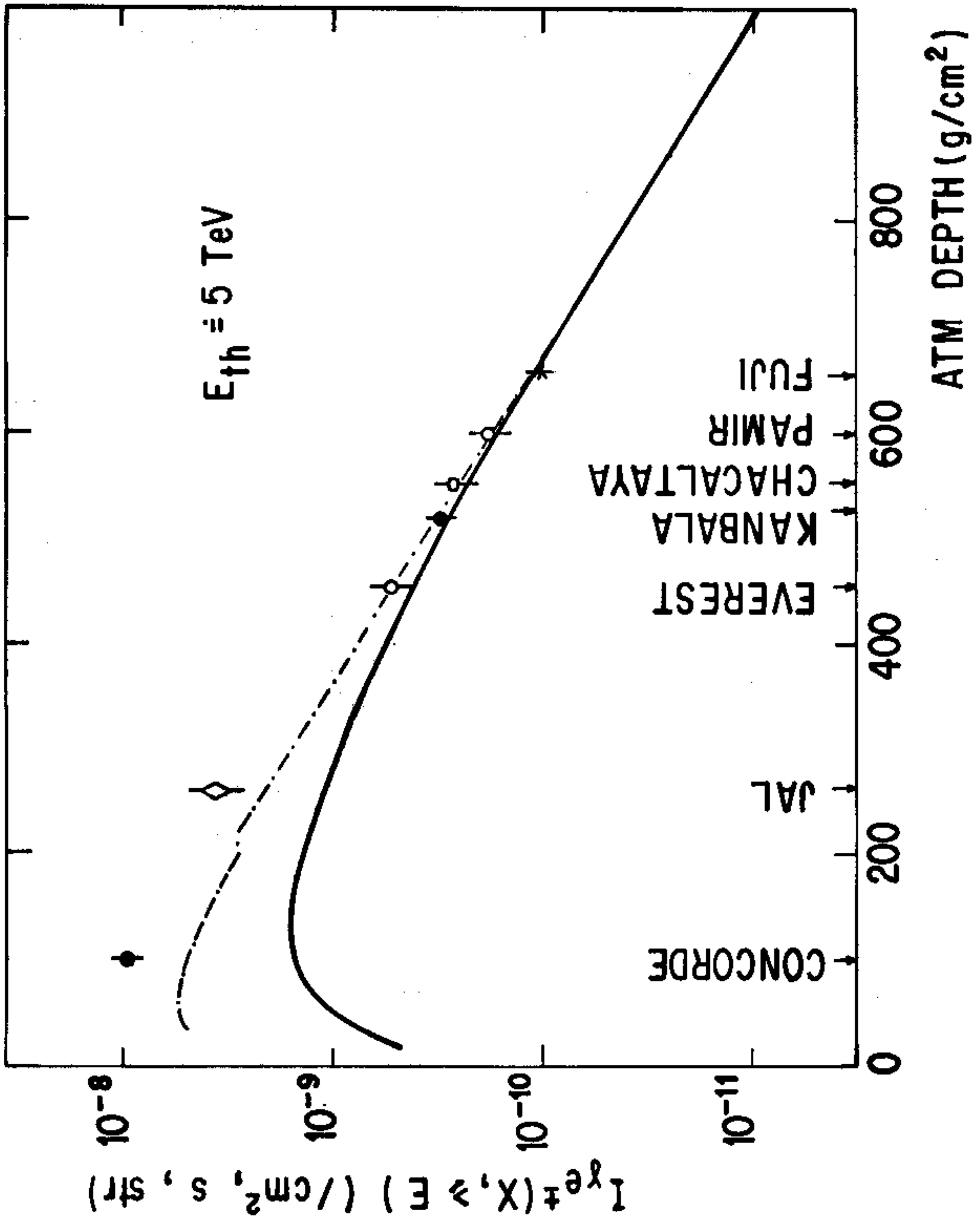
$E_{th} = 5$ TeV
$I_{\gamma e^{\pm}}(X, \geq E)$ (/cm², s, str)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ATM DEPTH (g/cm²)
0
200
400
600
800
CONCORDE
JAL
EVEREST
KANBALA
CHACALTAYA
PAMIR
FUJI

FIG.5

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