Temperature Effect of the Integral Flux of Cosmic-Ray Muons at High Energies

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Abstract—The temperature coefficients of the integral fluxes of cosmic-ray muons arriving at sea level vertically and horizontally with energies of $10^2$, $10^4$, and $3 \times 10^6$ GeV are calculated. Decays of pions, kaons, and charmed particles are considered as sources of muon generation in the atmosphere (according to current data on the generation cross sections of pions, kaons, and charmed particles in interactions between nucleons and the nuclei of atmospheric atoms, obtained in experiments on accelerators and in quantum chromodynamics models). The uncertainties in the generation cross sections of charmed particles are quite high.

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INTRODUCTION

The temperature effect of cosmic-ray muons was studied intensively in the 1950s, and is now being investigated (both experimentally and theoretically) on state-of-the-art setups all over the world.

We calculated the temperature coefficients of integral muon fluxes for energies up to $3 \times 10^6$ GeV according to data on pion, kaon, and charmed particle generation obtained experimentally on accelerators, and to the data on charm generation obtained in the quantum chromodynamics (QCD) models [1, 2].

INTEGRAL FLUX OF COSMIC-RAY MUONS

The equation for the integral muon flux in atmosphere can be written as

$$N_{\eta}(x, E_{\mu}, \theta) = B_{\eta} W_{\eta-\mu} I_{0\eta} \int E_{\mu}^{x} dE_{\mu} \int E_{\mu}^{x-x-\eta} \frac{\sigma_{\eta}}{c \tau_{\eta} P(t, \theta)} \left[ \exp \left( -\kappa_{\eta} x \right) + \int_{0}^{\eta} \tau_{\eta} \rho(\chi, \theta) E_{\mu}^{1-\gamma} d\chi \right]$$

if the primary differential nucleon spectrum $P_{N}(E_{N})dE_{N} = B_{N} E_{N}^{\gamma} dE_{N}$. Here, $E_{N}$ is the nucleon energy; $\gamma = 1.7$ ($B_{N} = 3.3$) for $E_{N} \leq 3 \times 10^6$ GeV and $\gamma = 2$ ($B_{N} = 290$) for $E_{N} \geq 3 \times 10^6$ GeV; $W_{\eta-\mu}$ is the probability of decay for an $\eta$ particle with muon formation; $E_{\mu}$ is the muon energy; $\mu = x, I, \phi, \chi$ are atmospheric depths expressed in terms of $\lambda_{0\eta}$ g cm$^{-2}$ ($\lambda_{0\eta}$ is the range of an $\eta$ particle in the atmosphere); $I_{0\eta}$ is the number of $\eta$ particles produced in a single interaction between nucleons and atmospheric atomic nuclei (the $I_{0\eta}$ values are reduced to their minimum (min) and maximum (max) values for the current data on, respectively, the minimum and maximum generation cross sections of charmed particles in interactions between nucleon and atmospheric atomic nuclei),

$$I_{0\eta} = \frac{\sigma_{N\eta}}{\sigma_{N\eta}(E_{N})} \int_{0}^{\nu} \frac{df(\nu)}{d\nu} d\nu,$$

$\sigma_{N\eta}(E_{N})$ is the cross section of interaction between nucleons and atmospheric atomic nuclei; $\sigma_{N\eta}$ is the generation cross section of $\eta$ particles in nuclear interactions between nucleons and atmospheric atomic nuclei; $\nu = E_{N} / E_{\eta}$ ($E_{\eta}$ is the $\eta$-particle energy); $df(\nu) / d\nu$ is the spectrum of generated $\eta$ particles according to
TEMPERATURE EFFECT OF THE INTEGRAL FLUX OF COSMIC-RAY MUONS

The sum of changes in the integral fluxes of muons is related to the change in the interaction of nucleons with nuclei of air atoms in atmosphere, with the decay of particles generating muons (pions, kaons, charmed particles) and the decay of muons with a change in atmospheric temperature.

TEMPERATURE COEFFICIENTS

Varying the integral muon spectra with respect to the air density, we find that

\[
\delta N_\eta(x, E_\mu, \theta) = B_\eta W_{\eta \rightarrow \mu} \int_0^{x(x-t)} \int_{E_\mu}^{E_\mu(x-t)} \frac{\eta\lambda_{\eta \rightarrow \mu}(x-t)}{E_\mu} \exp \left[ -\kappa_\eta \zeta + \zeta - t - \frac{\eta\lambda_{\eta \rightarrow \mu}}{c_\eta \rho(\chi, \theta \atop c_\eta \rho(x)} \right] \left[ \frac{d\chi}{\rho(\chi, \theta \atop c_\eta \rho(E_\mu, x)} \right] \right] d\zeta dE' dtdE_\mu'.
\]

Figures 1 and 2 show the results from our calculations (with allowance for pion, kaon, and charmed particle decays). The generation cross sections of charmed particles in the interactions between nucleons and atmospheric atomic nuclei are characterized by high uncertainties (the maximum and minimum generation cross sections of charmed particles, according to current experimental data obtained on accelerators and within QCD models, are presented in Figs. 1 and 2).

The temperature coefficients for the integral fluxes of cosmic-ray muons show the change in the integral muon flux at a certain depth in the atmosphere at \( \theta = 0^\circ \).