Effect of Primary Nuclei Composition on the Response Functions for Cosmic-Ray Muons.

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(received the 24 Luglio 1979)

Summary. — The integral response functions for cosmic-ray muons, at different muon threshold energies, are calculated by taking into account the nuclear composition of the primary cosmic radiation, and showing their contribution also at large zenith angles.

1. - Introduction.

To deduce the variations of primary particles, at the top of the atmosphere, from the measured muon intensities, it is essential to know the response function of the detectors, which represents the fraction of the muon intensity contributed by primaries of a given energy. Many authors (1), during the past years, have calculated different types of these functions, but the purpose of the present paper is to calculate the integral response functions, by taking into account also the nuclear composition of the primary cosmic rays. We shall adopt Feynman scaling as a model for the calculations of secondary spectra, so that the production cross-sections, determined from experiments at the highest available accelerator energies, can be scaled up to higher energies. To include also heavy primary nuclei (HN), we describe the production of secondaries (π, K) generating muons as due to three distinguished sources: a) interactions of nucleons derived from primary protons, b) interactions of secondary nucleons produced in HN collisions, and c) interactions of HN and fragmented nuclei with the air nuclei.

2. - Derivation.

The integral response function is defined as

\[ R(E_\mu, \theta, E_\mu) = \frac{I_\mu(E_\mu, z_0(\theta), E_\mu)}{I_\mu(E_\mu, z_0(\theta), E_\mu = \infty)} , \]

where \( I_\mu \) represents the intensity of muons with energy \( E_\mu > E_\mu_0 \), at sea level and at zenith angle \( \theta \), due to primaries with energy/nucleon \( E < E_\mu \). The analytical form of \( I_\mu \) is

\[ I_\mu(E_\mu, z_0, E) = \int_{E_\mu}^{E_\mu(\theta)} \int_{0}^{z_0} dE_\mu \int_{y(0)}^{E_\mu(y, \hat{y}(0))} W_{\mu}(E_\mu(y), z_0, y(\hat{y})) dy , \]

where \( W_{\mu} \) is the survival probability of muons in the atmosphere, and \( E_\mu(y) \) is the energy of a muon at \( y(\hat{y}) = y/\cos \theta \), reaching the sea level with energy \( E_\mu \). The maximum energy of a muon which may be produced at \( y(\hat{y}) \), by a primary of energy \( E_\mu \), is given by

\[ E_\mu^\mu(E_\mu) = \frac{E_\mu/r_\mu - az_0(\theta)}{b + az_0(\theta)} , \]

where \( r_\mu = m_\mu/m_\mu \), with \( s = \pi \) (pions) or \( s = K \) (kaons). The rate of energy loss which appears in eq. (3), and in the expression of \( W_{\mu} \) and \( E_\mu(y) \), is expressed by \(-dE_\mu/\hat{y} = a + bE_\mu\), where \( a \) and \( b \) correspond to the energy losses due to ionization and to the combined effects of radiation and pair creation.

The cascade model regarding fragmentation of HN, the release of nucleons from the HN collisions and the production and propagation of the \( \pi \) and \( K \) components in the atmosphere is described in detail elsewhere (\(^2\)). Using this model, we may express the differential muon flux as a sum of fluxes due to the sources described in sect. 1, that is \( F_\mu = \sum_{i=1}^{3} F_{\mu_i} \) (\( i = 1 \), incident protons; \( i = 2 \), secondary nucleons; \( i = 3 \) HN interactions). Every \( F_{\mu_i} \) is expressed by

\[ F_{\mu_i}[E_\mu(y), y(\hat{y})] = \frac{B_i}{E_\mu(y)} \cos \theta \sum_{k=i}^{3} \frac{J_{\mu_k}}{A_k} \int_{0}^{y} \frac{S_{\mu_k}(x_0, t, \theta)}{A_k} \exp \left[ \frac{-y(\hat{y})}{A_k} t(\hat{y}) \right] \left( \frac{t}{y} \right)^{b_k(\theta)} dt , \]