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ИССЛЕДОВАНИЕ СОГЛАСОВАННОСТИ ПОТОКА АТМОСФЕРНЫХ МЮОНОВ ВЫСОКИХ ЭНЕРГИЙ И СПЕКТРА ПЕРВИЧНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ ПО ДАННЫМ НОВЫХ ЭКСПЕРИМЕНТОВ

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STUDY OF CONSISTENCY OF A HIGH-ENERGY ATMOSPHERIC MUON FLUX AND PRIMARY COSMIC RAY SPECTRUM ON THE BASIS OF NEW EXPERIMENTS

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We calculate the cosmic ray muon flux at a ground level using directly the primary cosmic ray spectrum and composition measured in the ATIC-2 balloon experiment. In order to extend our calculations to higher energies, up to 100 TeV, we use the data of the GAMMA experiment as well as Zatsepin and Sokolskaya model. The muon flux computation is based on the method for solution of atmospheric hadron cascade equations in which rising total inelastic cross-sections of hadron-nuclear interactions as well as non-power-law character of the primary cosmic ray spectrum are taken into account. It is shown that the recent measurements of primary cosmic ray spectra are consistent with the recent experimental data on atmospheric muon fluxes at the ground level for a wide range of zenith angles. The calculated muon spectrum agrees well with measurements of L3+Cosmic, BESS-TeV, CAPRICE, Frejus, MACRO, LVD as well as other experiments. The comparison of the calculated muon flux with measured one also allowed us to evaluate muon flux uncertainties originated from primary spectrum measurement errors.

Introduction

The muons produced through cosmic ray interactions with the Earth atmosphere provide the tool for indirect study of the primary cosmic ray (PCR) spectra. May comparison of the predicted and measured atmospheric muon (AM) flux serve as a reliability trial for PCR data? The answer depends on the relationship between the size of the PCR uncertainties and that of AM flux. To attempt answering the question we calculate the cosmic ray muon flux at the ground level using directly the data on PCR spectrum and composition measured in the ATIC-2 experiment [1].

In order to compare the predictions with the high-energy measurements of the AM flux we extend the calculations to higher energies, up to 100 TeV, using also the PCR spectrum data of the GAMMA experiment [2]. The PCR model by Zatsepin and Sokolskaya [3] supported by the ATIC-2 data was applied as a nice instrument to extrapolate median energy data to high energy ones. This model comprises contributions to the cosmic ray flux of three classes of astrophysical sources like supernova and nova shocks. The muon flux calculation is based on the method to solve the atmospheric hadron cascade equations [4, 5] in which we take into account rising total inelastic cross-sections of hadron-nuclear interactions as well as non-power-law character of the primary cosmic ray spectrum. Hadron fluxes are computed with slightly revised Kimel and Mokhov parameterization (see [4, 6] for nucleon and meson production cross sections which are close to the SIBYLL mini-jet model [7]).

Primary cosmic ray spectra

The balloon borne experiment ATIC (Advanced Thin Ionization Calorimeter) [1], designed for measurements of cosmic rays energy spectra with individual charge resolution from protons to iron, enabled to obtain PCR spectra in the wide energy interval 50 GeV – 200 TeV with high statistical assurance. The differential spectra of protons and helium nuclei obtained in the ATIC-2 experiment are shown in Figure 1 along with a bulk of data from balloon, satellite and ground based experiments: BESS, AMS, IMAX, CAPRICE, MASS, RICH, MUBEE, RUNJOB, JACEE, SOKOL, KASCADE SH, GAMMA, HEGRA, TIBET HD, ICHIMURA (see [8] for the references).

Proton and helium spectra measured in the ATIC-2 experiment have different slopes and differ from a simple power law. The ATIC-2 data are in agreement with the data of magnetic spectrometers (BESS, AMS, IMAX, CAPRICE, MASS) below 100 GeV. In the energy region $1<E<10$ TeV the ATIC-2 data are consistent with the SOKOL measurements and with those of atmospheric Cherenkov light detector HEGRA. At energies above ~10 TeV the spectra become steeper and follow the data of emulsion chamber experiments MUBEE and JACEE though the agreement is not so clear. The solid curves in Figure 1 are to present the model suggested by Zatsepin and Sokolskaya (ZS) [3] that fits well the ATIC-2 experimental data and describe PCR spectra in the energy range 10–10^7 GeV. In order to extend our calculation to higher energies, the PCR spectra measured in the GAMMA [2] experiment were used. The energy spectra and elemental composition obtained in the GAMMA experiment cover the 10^3–10^5 TeV range (shaded areas) and agree with the corresponding extrapolations of known balloon and satellite

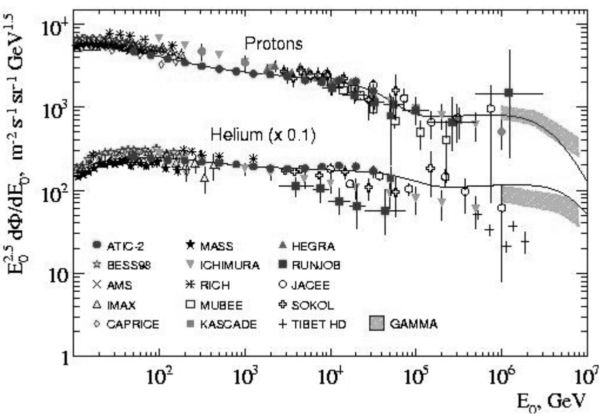

Fig. 1. Primary proton and helium spectra combining balloon, satellite and ground-based measurements. The solid curve presents Zatsepin and Sokolskaya model [33]. E_0 is the kinetic energy of the particle.

data at the $E \geq 10^3$ TeV. In the present calculation, a version of the spectra reconstructed in the framework of 1.2D combined analysis with the SIBYLL interaction model was utilized.

Model of the atmosphere

The Earth atmosphere is a natural environment in which primary cosmic rays interact with air nuclei and produce secondary particle fluxes, particularly muons and neutrinos. A good knowledge of the atmospheric density profile gives us an opportunity to calculate precisely the muon fluxes in a wide energy and zenith angles interval. This is important especially for the region of low/median energies and large zenith angles, where the slant depth becomes very large.

Atmospheric profile has been extensively studied during the past decades and, as a result, a number of models and parameterizations of experimental data have been published. In the present work we use the so-called US standard atmosphere parameterized according to the Linsley's model (see [9]). Supported by experiment, this model is widely used in the modern air-shower simulation codes CORSIKA, AIRES and others.

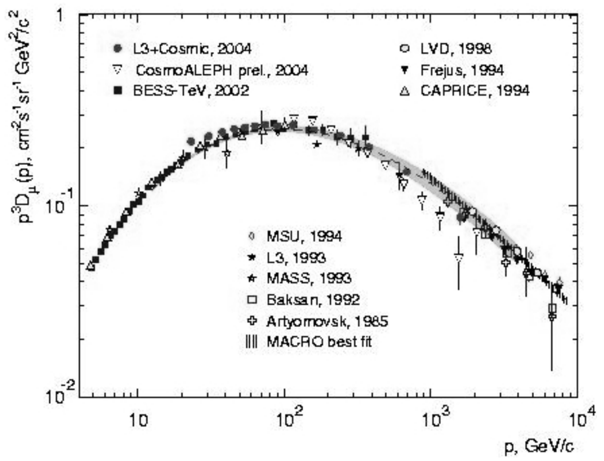

Fig. 2. Energy spectrum of muons at ground level near vertical. The dashed-line curves and the shaded area present this work calculation with the ATIC-2 primary cosmic-ray spectrum.

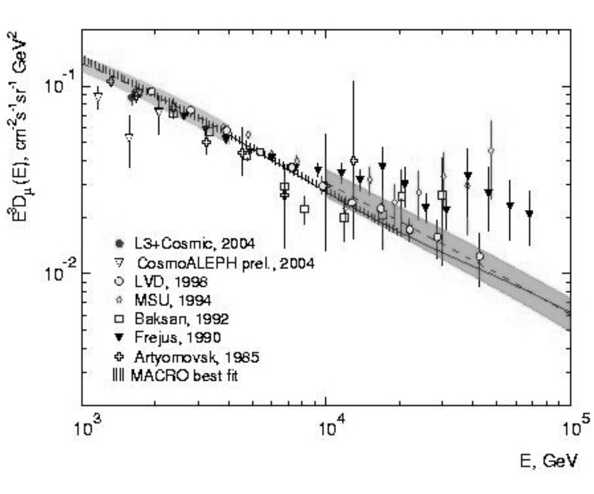

Fig. 3. High-energy plot of the ground level muon spectrum. The dashed-line curves and shaded areas present this work calculations with the ATIC-2 primary spectrum (left) and GAMMA one (right). The solid curve presents the calculation with Zatsepin and Sokolskaya model.

The quantity that naturally describes the varying density of the atmospheric medium is the "vertical atmospheric column depth" h_v (in units of g/cm^2). It is equal to the pressure of the atmosphere above the altitude H in a vertical direction:

$$h_v(H) = \int_H^{\infty} \rho(H)\,dH,$$

here $\rho(H)$ is a density of air at the given altitude H. In the Linsley's model, the atmosphere is divided into L layers and parameterized as follows:

$$h_v(H) = \begin{cases} a_l + b_l e^{-H/c_l}, & H_l \leq H < H_{l+1}, l = 1, \ldots, L-1 \\ a_L - b_L(H/c_L), & H_L \leq H < H_{L+1} \\ 0, & H \geq H_{L+1}. \end{cases}$$

A standard set of parameters a_l, b_l, c_l with L=5 taken from [9] is presented in Table. It is clearly seen that the first layer (l = 1) starts from the altitude H_1 = 0 km and the maximum altitude is defined as follows $H_{L+1} = H_{\max}$ = =113 km.

Parameters of the US standard atmosphere according to the Linsley's model

L	Altitude interval (km) from–to	a_l (g/cm^2)	b_l (g/cm^2)	c_l (m)
1	0–4	–186.5562	1222.6562	9941.8638
2	4–10	–94.9199	1144.9069	8781.5355
3	10–40	0.61289	1305.5948	6361.4304
4	40–100	0.0	540.1778	7721.7016
5	100–113	0.01128292	1	10^7

Energy spectra and zenith angle distributions of atmospheric muons

Apart from evident sources of AM, $\pi_{\mu2}$ and $K_{\mu2}$ decays, we take into consideration three-particle semileptonic decays, $K^{\pm}_{\mu3}$, $K^0_{\mu3}$. Also we take into account small fraction of the muon flux originated from decay chains $K \to \pi \to \mu$ $\left(K^0_S \to \pi^+ + \pi^-, \quad K^{\pm} \to \pi^{\pm} + \pi^0, \quad K^0_L \to \pi^{\pm} + \ell^{\mp} + \bar{\nu}_{\ell}(\nu_{\ell}), \ \ell = e, \mu\right)$. We do not consider here a conjectural prompt muon component of the flux (see e.g. [10, 11]). In Figures 2, 3 presented are results of the calculation of the surface muon flux near horizontal along with the data of muon experiments that comprise the direct measurements of CAPRICE [12], BESS-TeV [13], L3+Cosmic [14], Cosmo-ALEPH (see [15]), L3 and MASS (are taken from [10]) as well as the data (converted to the surface) of underground experiments MSU [16], MACRO [17], LVD [18], Frejus [19], Baksan [20], Artyomovsk [21]. The light shaded areas in Figures 2, 3 (the left corner) show the muon spectrum calculated with the ATIC-2 primary spectra taking into consideration statistical errors (dashed curve corresponds to mean values). For the range 10–3000 GeV one can see fair accordance of the muon flux calculations using ATIC-2 spectra with the recent measurements. The high-energy part of the muon flux is shown in Figure 3, where the dark shaded area (at the right) presents our calculation for the GAMMA primary spectra and the solid curve presents the muon flux computed for ZS primary spectrum model which appears to be a reliable bridge from

TeV range to PeV one. It should be noted, that without considering the prompt muon contribution above 10 TeV, one can say about satisfactory agreement of calculated fluxes only with the data of MACRO and LVD measurements. Our computations of the vertical muon flux for other PCR spectra models as well as comparison with calculations of other authors were presented in [5, 22].

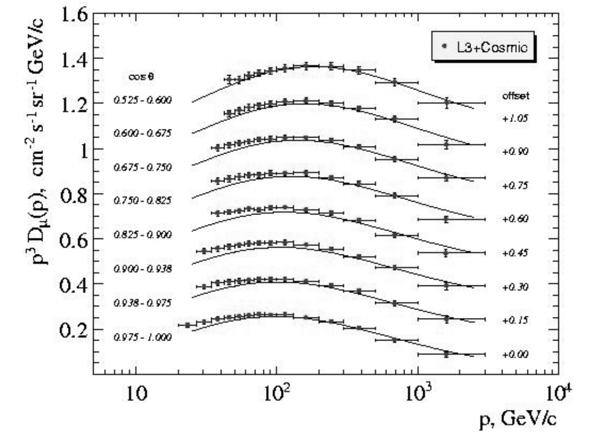

Fig. 4. Calculated atmospheric muon energy spectrum and recent results of L3+Cosmic experiment for zenith angles 0–58º. Calculations are performed for the ATIC-2 primary cosmic ray spectra. Solid curves correspond to the average zenith angles for given angle bin.

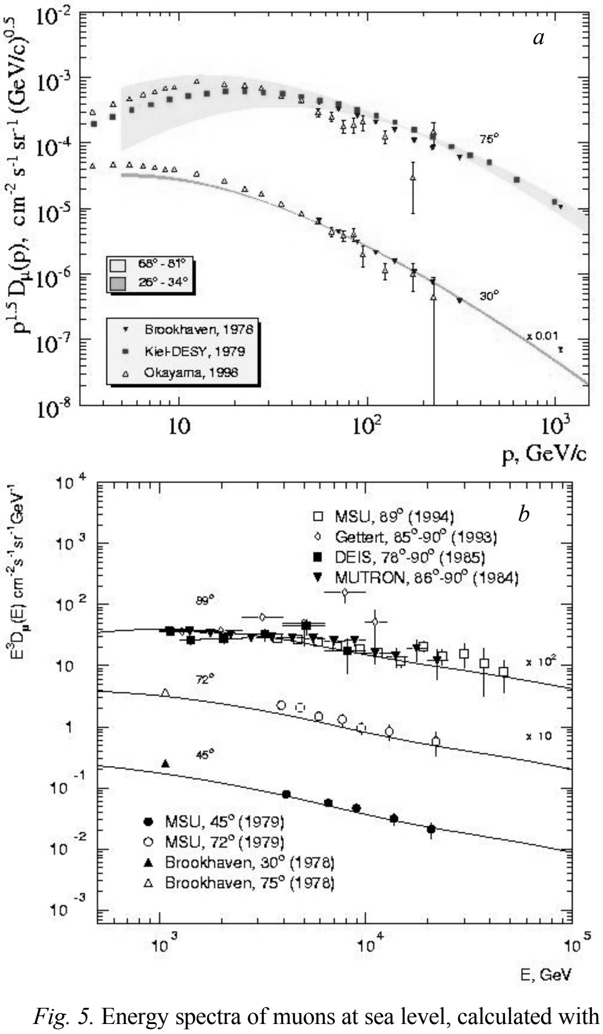

Fig. 5. Energy spectra of muons at sea level, calculated with the ATIC-2 spectra for several zenith angles: θ=30, 75º (*a*); θ=45, 72, 89º (*b*). The filled areas display the expected flux variations due to angle uncertainties in measurement data (see text).

Using essentially the same procedure [5] we perform the calculation of atmospheric muon energy/momentum spectra for different zenith-angle intervals (Figures 4, 5). To compare our computation with recent L3+Cosmic experiment for the zenith angle range $0° \le \theta \le 58°$ (Figure 4) the atmospheric density profile measured nearly the site of L3+Cosmic experiment was applied. Our result qualitatively agrees with the shape of the L3+Cosmic measurements for the momentum range $p \ge 50$ GeV. The flux normalization for the $p < 50$ GeV determined by the L3 + Cosmic experiment seems to be systematically higher than our calculation. The possible reason of this slight discrepancy may be related to the consideration of the energy loss of low energy muons within 30 m molasse overburden, located under the L3+Cosmic detector.

To compare with experiments MSU [16, 23], DEIS [24], MUTRON [25], Brookhaven [26], Kiel-DESY[27], Gettert [28], Okayama [29], we have performed the computation for the zenith angle range 30–89º (Figure 5), using the Linsley's parameterization of the US standard atmosphere. The calculated muon spectrum agrees well with these measurements within experimental errors.

Conclusions

The present calculations demonstrate the consistency of the new primary comic ray spectra measurements with the recent experimental data on atmospheric muon fluxes at the ground level for a wide energy range and zenith-angle intervals. The muon spectrum calculation based directly on the primary cosmic ray spectrum and mass composition measured by the ATIC-2 balloon experiment agrees well with measurements of L3+Cosmic, BESS-TeV, CAPRICE, Frejus, MACRO, LVD, as well as other experiments. The comparison of the calculated muon flux with measured one also allowed us to evaluate muon flux uncertainties originated from the primary spectrum measurement errors. It is shown that the high accuracy of the ATIC-2 data results in the muon flux calculation uncertainty, comparable with rather high precision of the last decade muon flux measurements.

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