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Atmospheric neutrino flux and muon data

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Abstract. We present a new one-dimensional calculation of low and intermediate energy atmospheric muon and neutrino fluxes, using up-to-date data on primary cosmic rays and hadronic interactions. The existing agreement between calculated muon fluxes and the data of the CAPRICE 94 muon experiment provides an evidence in favor of the validity of our description of hadronic interactions and shower development. This also supports our neutrino fluxes which are essentially lower than those used for the standard analyses of the sub-GeV and multi-GeV neutrino induced events in underground detectors.

1 Introduction

In this work we present some results of a new calculation of low and intermediate energy muon and neutrino fluxes based on up-to-date data on primary cosmic-ray flux and hadronic interactions. In order to demonstrate the validity of our approach, we give a comparison of the predicted muon fluxes with the recent data by the CAPRICE 94 balloon-borne experiment (Boezio et al., 2000).

Our calculations are based on an updated code CORT (Fiorentini et al., 2001). Like the earlier version (see Bugaev and Naumov (1987, 1989, 1990) and references therein) the new code implements a numerical solution of a system of one-dimensional (1D) kinetic equations describing the propagation of cosmic-ray nuclei, nucleons, π and K mesons, muons, neutrinos, and antineutrinos of low and intermediate energies through a spherical, nonisothermal atmosphere.

In order to evaluate geomagnetic effects and to take into account the anisotropy of the primary cosmic-ray flux in the vicinity of the Earth, we use the method by Naumov (1984) and detailed maps of the effective vertical cutoff rigidities by Dorman et al. (1971). The maps are corrected for the geomagnetic pole drift and compared with the later results reviewed by Smart and Shea (1994) and with the recent AMS data on the proton flux in near earth orbit (Alcaraz et al., 2000). The interpolation between the reference points of the maps is performed by means of two-dimensional local B-spline. The Quenby-Wenk relation (Dorman et al., 1971), renormalized to the vertical cutoffs, is applied for evaluating the effective cutoffs for oblique directions. More sophisticated effects, like the short-period variations of the geomagnetic field, Forbush decrease, re-entrant cosmic-ray albedo contribution, etc., are neglected. We also neglect the geomagnetic bending of the trajectories of charged secondaries and multiple scattering effects. Validity of our treatment of propagation of secondary nucleons and nuclei was confirmed using all available data on the proton and neutron spectra in the atmosphere (Naumov, 1984; Bugaev and Naumov, 1985).

The meteorological effects are included using the Dorman model of the atmosphere (Dorman, 1971) which assumes an isothermal stratosphere and constant gradient of temperature (as a function of depths) below the tropopause. Ionization, radiative and photonuclear muon energy losses are treated as continuous processes. This approximation is quite tolerable for atmospheric depths $h \lesssim 2 \times 10^3$ g/cm^2 at all energies of interest (Naumov et al., 1994). Propagation of μ^+ and μ^- originating from every source (pion or kaon decay) is described by separate kinetic equations for muons with definite polarization at production. These equations automatically account for muon depolarization through the energy loss (but not through the Coulomb scattering).

2 Primary cosmic ray spectrum and composition

In the present calculations, the nuclear component of primary cosmic rays is broken up into 5 principal groups: H, He, CNO, Ne-S and Fe with average atomic masses A of 1, 4, 15, 27 and 56, respectively. We do not take into account the isotopic composition of the primary nuclei and assume $Z = A/2$ for $A > 1$, since the expected effect on the secondary lepton fluxes is estimated to be small with respect to present-day experimental uncertainties in the abso-

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lute cosmic-ray flux and chemical composition.

We parametrize the spectra of the H and He groups at $E < 120$ GeV/nucleon by fitting the data of the balloon-borne experiment BESS obtained by a flight in 1998 (Sanuki et al., 2000). For higher energies (but below the knee) we use data by a series of twelve balloon flights of JACEE (Asakimori et al., 1998) and the result of an analysis by Wiebel-Sooth et al. (1998) based upon a representative compilation of world data on primaries. We assume that the spectra of the remaining three nuclear groups are similar to the helium spectrum. This assumption does not contradict the world data for the CNO and Ne-S nuclear groups but works a bit worse for the iron group. Nevertheless, a more sophisticated model would be unpractical since the corresponding correction would affect the secondary lepton fluxes by a negligible margin.

In this paper we do not consider the effects of solar modulation. Therefore the predicted muon and neutrino fluxes are to some extent the maximum ones possible within our approach.

3 Nucleon-nucleus and nucleus-nucleus interactions

All calculations with the earlier version of CORT (see, e.g., Naumov (1984); Bugaev and Naumov (1985, 1987, 1989, 1990); Bugaev et al. (1998)) were based on semiempirical models for inclusive nucleon and meson production in collisions of nucleons with nuclei by Kimel' and Mokhov (1974, 1975); Serov and Sychev (1973).[1] The Kimel'-Mokhov (KM) model is valid for projectile nucleon momenta above ~ 4 GeV/c and for the secondary nucleon, pion and kaon momenta above 450, 150 and 300 MeV/c, respectively. Outside these ranges (that is mainly within the region of resonance production of pions) the Serov-Sychev (SS) model was used.

Both models are in essence comprehensive parametrizations of the relevant accelerator data. In our opinion, the combined "KM+SS" model provides a rather safe and model-independent basis to the low-energy atmospheric muon and neutrino calculations. However it is not free of uncertainties. For the present calculation, the fitting parameters of the KM model for meson and nucleon production off different nuclear targets were updated using accelerator data not available for the original analysis (Kimel' and Mokhov, 1974, 1975; Kalinovsky et al., 1985). The values of the parameters were extrapolated to the air nuclei (N, O, Ar, C). The overall correction is less than 10-15% within the kinematic regions significant to atmospheric cascade calculations. Besides that energy-dependent correction factors were introduced into the model to tune up the output π^+/π^- ratio taking into account the relevant new data.

The processes of meson regeneration and charge exchange ($\pi^{\pm} + \mathrm{Air} \to \pi^{\pm(\mp)} + X$ etc.) are not of critical importance for production of leptons with energies of our interest and can be considered in a simplified way. Here we use a proper renormalization of the meson interaction lengths, which was deduced from the results by Vall et al. (1986) obtained for high-energy cascades.

The next important ingredient of any cascade calculations is a model for nucleus-nucleus collisions. Here we consider a modest generalization of a simple "Glauber-like" model used in (Naumov, 1984; Bugaev and Naumov, 1985). Namely, we write the inclusive spectrum of secondary particles c ($c = p$, n, $\pi^{\pm}$, $K^{\pm}$, $K^0, \ldots$) produced in AB collisions as

$$\begin{aligned}\frac{dN_{\mathrm{AB}\to cX}}{dx} =& \xi^c_{\mathrm{AB}}\left[Z\frac{dN_{p\mathrm{B}\to cX}}{dx} + (A-Z)\frac{dN_{n\mathrm{B}\to cX}}{dx}\right] \\ &+ (1-\xi^c_{\mathrm{AB}})\left[Z\delta_{cp} + (A-Z)\delta_{cn}\right]\delta(1-x).\end{aligned}$$

Here $dN_{N\mathrm{B}\to cX}/dx$ is the spectrum of particles c produced in NB collisions ($N = p, n$) and ξ^c_{AB} is the average fraction of inelastically interacting nucleons of the projectile nucleus A. The term proportional to delta function describes the contribution of "spectator" nucleons from the projectile nucleus.

In the standard Glauber-Gribov multiple scattering theory the quantity ξ^c_{AB} is certainly independent of the type of inclusive particle c. On the other hand, it depends of the type of nucleus collision. Indeed, essentially all nucleons participate in the central AB collisions ($\xi^c_{\mathrm{AB}} \simeq 1$)[2] while, according to the well-known Bialas–Bleszyński–Czyż (BBC) relation (Bialas et al., 1976), $\xi^c_{\mathrm{AB}} = \sigma^{\mathrm{inel}}_{N\mathrm{B}}/\sigma^{\mathrm{inel}}_{\mathrm{AB}}$ for the minimum bias collisions.

To use the above model in a cascade calculation one should take into account that nucleons and mesons are effectively produced in nuclear collisions of different kind. Namely, the contribution from central collisions is almost inessential for the nucleon component of the cascade but quite important for light meson production. Thus one can expect that effectively $\xi^{\pi,K}_{\mathrm{AB}} > \xi^{p,n}_{\mathrm{AB}}$. We use the BBC relation for nucleon production by any nucleus while for meson production we put $\xi^{\pi,K}_{\mathrm{He-Air}} = \xi$, where ξ is a free parameter. Variations of this parameter within the experimental limits yield a comparatively small effect to the muon fluxes (except for very high altitudes) and inessential ($\lesssim 6\%$) effect to the neutrino fluxes at sea level (Fiorentini et al., 2001). Effect of similar variations of the parameters $\xi^{\pi,K}_{\mathrm{A-Air}}$ for other nuclear groups is completely negligible. Below, we use the fixed value $\xi = 0.685$.

4 Numerical results and discussion

In Fig. 1 we compare the calculated momentum spectra of μ^+ and μ^- for twelve atmospheric depths with the data of the balloon-borne experiment CAPRICE 94 (Boezio et al., 2000). The values of depths indicated in Fig. 1 are the Flux-weighted Average Depths (FAD) (Boezio et al., 2000) for 11 atmospheric ranges Δh_i ($h_i < 10^3$ g/cm^2).[3] Figure 1 also includes the result of the recent 3D calculation by Battistoni

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[1] See also Kalinovsky et al. (1985); Sychev (1999) for the most recent versions.

[2] Here we suppose for simplicity that the atomic weight of the projectile nucleus is not much larger than that of the target nucleus.

[3] We neglect the small spreads of the FADs within some of the ranges Δh_i.

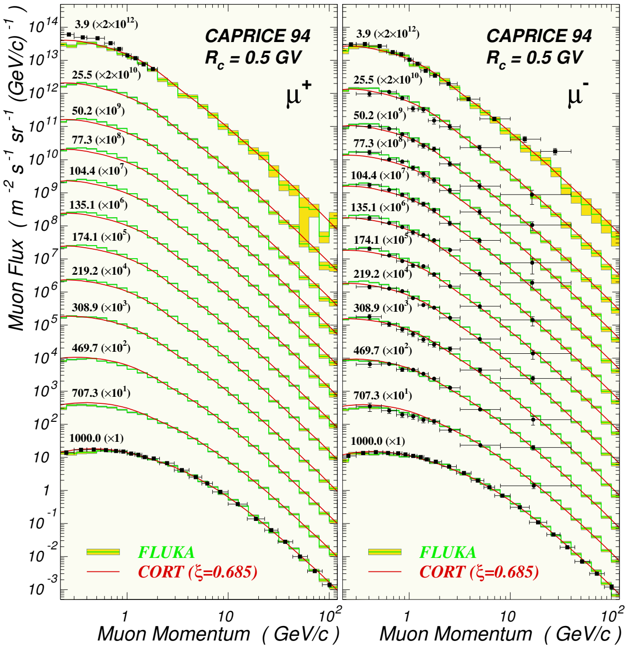

Fig. 1. Differential momentum spectra of μ^+ and μ^- for 12 atmospheric depths. The data points are from CAPRICE 94 experiment (Boezio et al., 2000). The curves and histograms are calculations with CORT and FLUKA, respectively, performed for the conditions of the experiment. The numbers indicate the FAD (in g/cm^2) and scale factors (in parentheses).

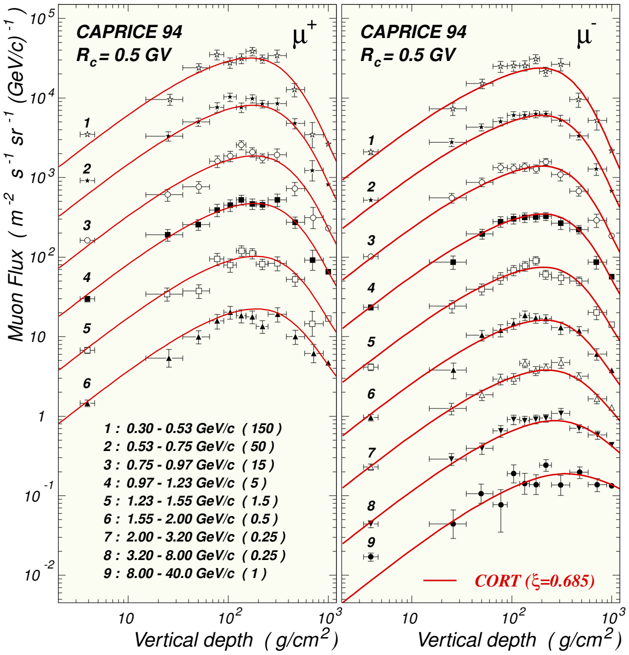

Fig. 2. Atmospheric growth curves for μ^+ and μ^-. The data points are from the CAPRICE 94 experiment (Boezio et al., 2000). The curves are calculations with CORT performed for the conditions of the experiment. The legend shows the muon momentum bins and scale factors (in parentheses) for both panels.

(2001) based on the FLUKA 3D Monte Carlo code (Battistoni et al., 2000). Figure 2 shows the atmospheric growth of muon fluxes for six momentum bins for μ^+ and nine bins for μ^-. The CAPRICE 94 data (Boezio et al., 2000) are compared with our calculations performed for the same bins.

From Figs. 1 and 2, one concludes that there is a substantial agreement between the CORT predictions and the current muon data within wide ranges of muon momenta and atmospheric depths. In particular, the agreement is good for the region of effective production of leptons (100–300 g/cm^2), in which the spread of the data is minimal. This provides an evidence for the validity of our nuclear-cascade model. The comparison between CORT and FLUKA presented in Fig. 1 demonstrates a very good agreement (see also the result by Poirier et al. (2001) obtained with FLUKA).

Now, let us consider our results for atmospheric neutrino (AN) fluxes for the nine underground laboratories listed in Fig. 3. Figure 4 shows the ν_e, $\overline{\nu}_e$, ν_μ and $\overline{\nu}_\mu$ energy spectra averaged over all zenith and azimuth angles. The ratios of the AN fluxes averaged over the lower and upper semispheres ("up-to-down" ratios) are shown in Fig. 5. As a result of geomagnetic effects, both the spectra and the up-to-down ratios are different for different underground neutrino experiments.

Below 1-2 GeV our calculations lead to AN fluxes which are essentially lower than those obtained by Barr et al. (1989) and by Honda et al. (1990) and those are used in many analyses of the sub-GeV and multi-GeV ν induced events in underground detectors. On the other hand, our fluxes are rather close to the results obtained with the earlier version of CORT (Bugaev and Naumov, 1987, 1989, 1990). The AN fluxes and angular distributions calculated with CORT and FLUKA are in a good agreement above 0.7–0.8 GeV (the difference is typically $\lesssim 15\%$) and disagreement (up to 30–40%) at lower energies. A comparison between the earlier calculations of the AN fluxe is discussed by Gaisser et al. (1996).

Here we do not discuss the complex problem of the interpretation of the AN anomaly[4] in the light of our result. However, we remark that our low AN flux, when it is applied to the analysis of the underground neutrino data, results in some electron excess together with (or rather than) the muon deficit in the ν induced events. We emphasize that in the con-

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[4] For a recent review see Ref. (Kajita and Totsuka, 2001).

Lab/Detector	Country	Geographical location		Geomagnetic location		Token
SOUDAN	USA	48.00°N	92.00°W	58.32°	331.78°	• • •
IMB	USA	41.72°N	81.27°W	52.83°	346.30°	——
HPW	USA	40.60°N	111.00°W	48.71°	311.28°	▴ ▴ ▴
NUSEX	Italy	45.86°N	6.90°E	47.24°	89.09°	▾ ▾ ▾
Fréjus	France	45.14°N	6.69°E	46.59°	88.59°	- - - - -
Gran Sasso	Italy	42.45°N	13.57°E	42.64°	94.27°	....
Baksan	Russia	43.30°N	42.70°E	38.06°	121.64°	⋆ ⋆ ⋆
Kamioka	Japan	36.42°N	137.31°E	26.19°	204.48°	-·-·-
KGF	India	3.00°N	78.30°E	3.25°	149.36°	▪ ▪ ▪

Fig. 3. List of some underground laboratories.

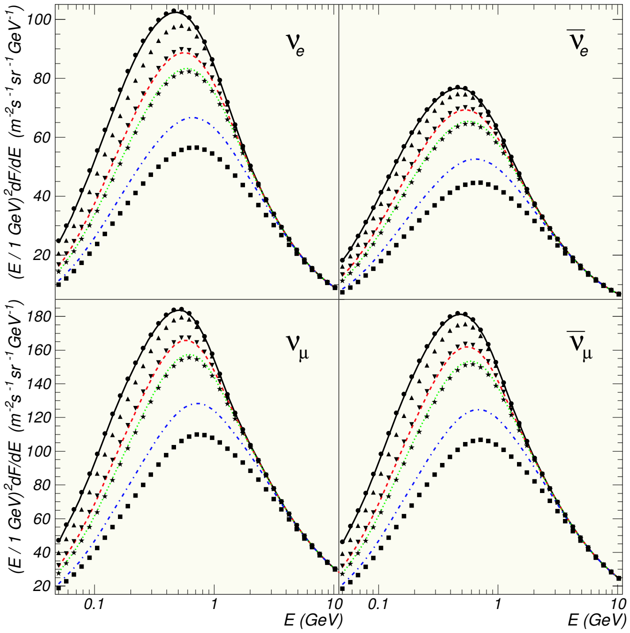

Fig. 4. Scaled 4π averaged fluxes of ν_e, $\overline{\nu}_e$, ν_μ, and $\overline{\nu}_\mu$ for nine underground laboratories (see Fig. 3 for the notation).

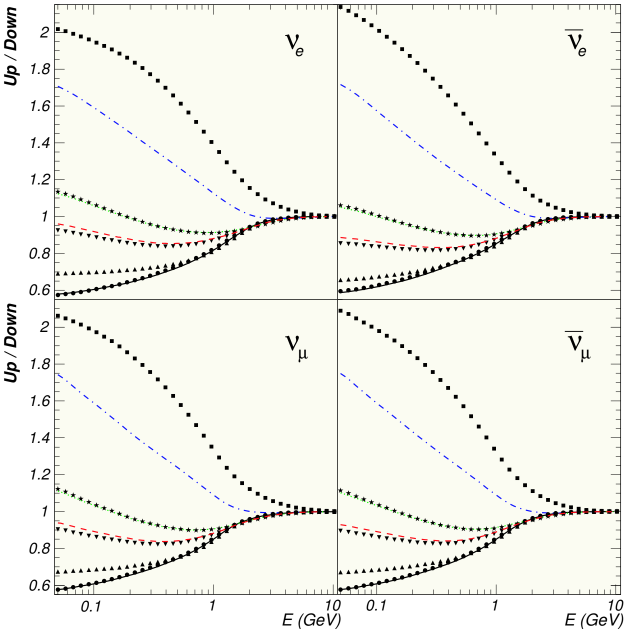

Fig. 5. Up-to-Down ratios of the ν_e, $\overline{\nu}_e$, ν_μ, and $\overline{\nu}_\mu$ fluxes for nine underground laboratories (see Fig. 3 for the notation).

text of our model it is difficult to increase the AN flux without spoiling the agreement with the current data on muon fluxes, hadronic cross sections, and primary cosmic-ray spectrum.

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