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Muon flux in the atmosphere at solar activity minimum

V. S. MAKHMUTOV[1], Y. I. STOZHKOV[1], N. S. SVIRZHEVSKY[1], L. DESORGHER[2], E. FLÜCKIGER[2]
[1] *Lebedev Physical Institute Russian Academy of Sciences, Moscow, Russia*
[2] *Physicalishes Institut, University of Bern, CH-3012 Bern, Switzerland*
makhmutv@sci.lebedev.ru

Abstract: Measurements of muon flux in the atmosphere have been performed by Lebedev Physical Institute during the Antarctic sea expedition in November 1975 – March 1976 period. This survey covered a wide range of latitudes with geomagnetic cutoff rigidities R_c from 0.8 up to 14.2 GV. The data on muon flux as function of atmospheric depth (X~ 10-1000 g·cm^{-2}) were obtained. On the other hand, based on GEANT4 facilities we have calculated the secondary muon fluxes produced by Galactic Cosmic Rays (GCRs) in the atmosphere at different R_c during solar activity minimum epoch. The experimental and calculation results as well as their comparison are presented in the paper.

Introduction

Set of balloon measurements of muon flux in the atmosphere was performed by Lebedev Physical Institute, Russian Academy of Sciences in Antarctic sea expedition at several locations during solar activity minimum (in November 1975 - March 1976). The measurements were carried out at atmospheric depths of 10 - 1000 g·cm^{-2} with a detector consisting of Geiger counters and a lead filter separating them. To compare the experimental results and expected ones we simulated Galactic Cosmic Rays transport in the atmosphere using the PLANETOCOSMICS code based on GEANT4 [1,2,3]. Both experimental data on muon fluxes distribution in the atmosphere and results of simulation are very important to analyze GCR hadronic interaction features, effect of geomagnetic field (especially in the low momentum range of muons), estimations of neutrino fluxes in the atmosphere, etc. [e.g. 4,5,6,7].

Experimental data

We measured absolute muon fluxes in the atmosphere using detector consisted of 8 Geiger counters (1.9 cm in diameter and 9.8 cm in length; 0.05 g·cm^{-2} steel walls) separated by lead (*Pb*) filter of 2.5 cm thickness (Figure 1). The device output was organized in 3 channels: CH1 is a count rate of a single counter 2 only, CH2 is a

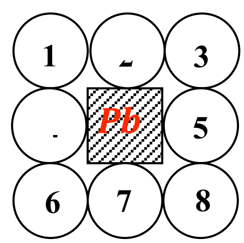

Figure 1: A detector scheme: eight Geiger counters (1-8) arranged as a vertical telescope, with a 2.5 cm thick *Pb* filter in the center.

count rate of particles passing through the counters 2 and 7, and CH3 is a count rate of simultaneous pulses in counters 2, 7 and in any of counters 1, 3, 4-6 or 8. In this way we separate omnidirectional flux of ionizing particles (CH1), air showers (CH3) and hard cosmic ray component (muons with energy >100 MeV and protons) in the atmosphere. In this paper we present observational results on muon flux

Table: Geomagnetic locations of the cosmic ray ballooning during sea expedition in November 1975 - March 1976. In parenthesis is a number of balloon flights at each location.

#	Mean R_c (GV)	Geomagnetic cutoff rigidity of locations and balloon flight numbers
1	1.0	1.14 (2); 0.88 (2)
2	2.4	2.40 (1)
3	4.5	4.81(2); 4.70 (1); 4.49 (2)
4	7.6	8.00(2); 7.30 (1); 7.02 (1); 7.64(2)
5	8.3	7.02 (1); 7.30 (1); 7.64 (2); 8.00 (2); 9.44 (1); 9.75 (2)
6	11.3	11.09 (1); 11,39 (1); 11.79 (2); 12.62 (1)
7	13.6	13.17 (2); 13.43 (1); 13.98 (1); 14.17 (1)

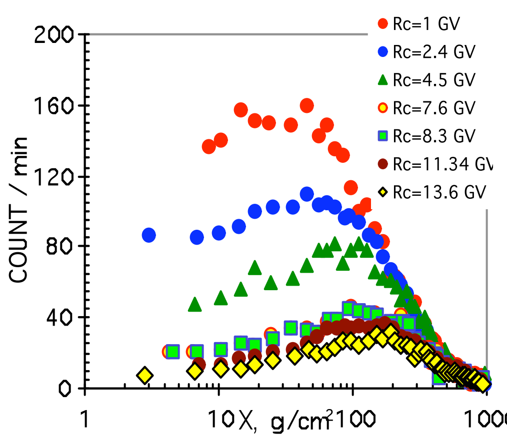

Figure 2: Count rate of > 100 MeV muons as a function of atmospheric depth at several locations (R_c=1÷13.6 GV) during solar activity minimum (November 1975 - March 1976 period).

distribution in the atmosphere at several geographical (geomagnetic) locations (see Table). We used data recorded by CH2 of the device, which relate to the measurements of >100 MeV muons (N) and primary particles of GCRs (N_{pr}) in the atmosphere. A primary flux contribution at different levels of atmospheric depth (X) can be expressed in the form $N_{pr}=N_o\exp(-X/X_o)$, where N_o is a primary cosmic ray flux (e.g. N_o=100 cm^{-2} s^{-1}sr^{-1} at location of R_c=13.6 GV) and characteristic absorption length X_o=100 g·cm^{-2}. Then the difference $N=N_{tot}-N_{pr}$ will represent the muon flux contribution in the total count rate N_{tot} of channel CH2 at selected level X in the atmosphere. Thus muon flux absorption curve in the atmosphere at several locations was estimated from our experimental data (see Figure 2). It allows to determine important features of atmospheric muon flux spatial distribution, namely: (1) count rate maximum of muon flux in the atmosphere depends on the geomagnetic cutoff rigidity of the location (R_c) as N_{max}(min^{-1})= 149.12 - 48.12ln(R_c) (see Figure 3). The ratio of

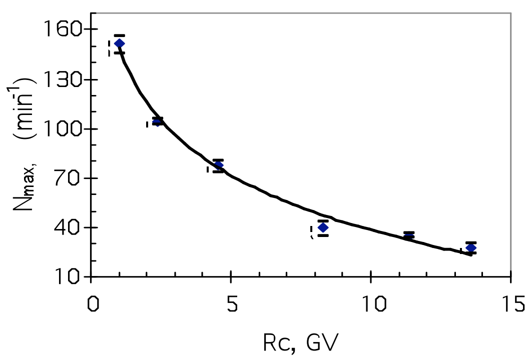

Figure 3: Maximum > 100 MeV muons count rate in the atmosphere as a function of the R_c of geomagnetic location.

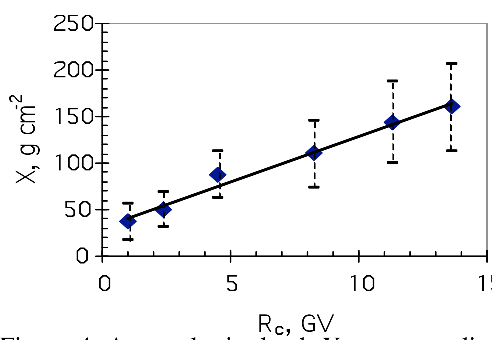

Figure 4: Atmospheric depth X corresponding to the maximum of muon flux in the atmosphere as a function of geomagnetic cutoff rigidity (R_c) of location.

$N_{max}(R_c=1\ GV)/N_{max}(R_c=13.6\ GV)$ is equal to 6.3 (2) maximum of > 100 MeV muon absorption curve position in the atmosphere X depends on the cutoff rigidity of the location (R_c) as $X(g\cdot cm^{-2})=9.8R_c(GV)+31.3$ For example, the maximum position shifts from X≈40 $g\cdot cm^{-2}$ at R_c≈1 GV to X≈150 $g\cdot cm^{-2}$ at R_c=13.6 GV (Figure 4). Also we note the muon flux maximum position in the atmosphere should not depend on R_c below R_c≈1-1.5 GV.

Simulation of the proton transport in the atmosphere

We simulated the interaction of galactic cosmic ray population - protons with the Earth's atmosphere using the Monte Carlo PLANETOCOSMICS code based on Geant4 [1-4; cosray.unibe.ch/~laurent/planetocosmics]. The code takes into account the following processes: bremsstrahlung, ionization, multiple scattering, pair production, Compton scattering, photoelectric effect, elastic and inelastic nuclear interaction, and the decay of particles. In previous studies we show a validity of the PLANETOCOSMICS code application in analysis of balloon observations in the atmosphere during solar proton events and precipitations of magnetospheric electrons into the Earth's atmosphere [e.g. 8,9,10]. In this paper the GCR proton component is considered as isotropic at the top of the atmosphere and their energy spectra at solar activity minimum was described by equation $J(E)[\#/m^2\cdot s\cdot sr\cdot MeV] = D\cdot E^{\alpha}/(0.01E+B)^4 + C\cdot \exp(-0.01E)$, where E is proton kinetic energy (MeV), D=16, B=8,α=1.3 and C=1.1 [11]. The primary proton energy range of 10 - 10^6 MeV was chosen in simulation. We compute the upward and downward fluxes of secondary protons, electrons, positrons, photons (gamma), pions and muons for 28 atmospheric depth levels from the ground up to the top of the atmosphere (X = 0.05, 5, 10, …, 1000 $g\cdot cm^{-2}$). The energy spectra of these secondaries were calculated at selected atmospheric levels (see Figure 5 for muon spectra). Finally we calculated > 100 MeV muon absorption spectra in the atmosphere. Figure 6 shows comparison of

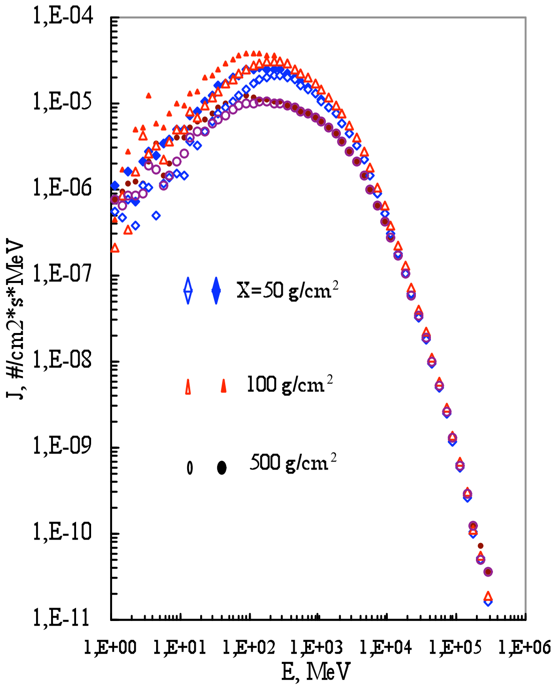

Figure 5: Result of simulation: muon differential energy spectra at several atmospheric levels X (50,100 and 500 $g\cdot cm^{-2}$) at location with R_c=13.6 GV. The omnidirectional fluxes (integration over 4π) and downward fluxes coming from 2π angle are shown by filled and open symbols, correspondingly.

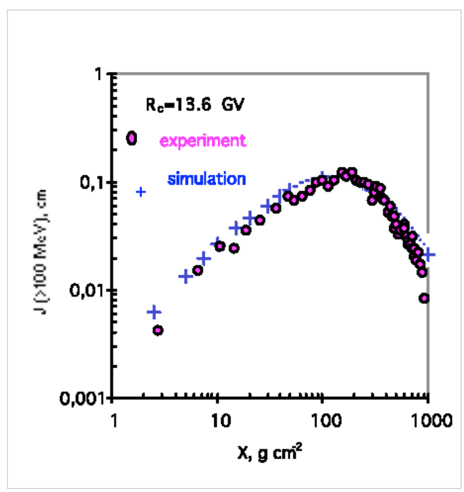

Figure 6: Comparison of experimental data and simulation results: muon flux (E>100 MeV) absorption spectra in the atmosphere at geomagnetic location with R_c=13.6 GV.

experimental data and results of Monte Carlo simulation related to > 100 MeV muon flux at geomagnetic location R_c=13.6 GV. To determine muon flux from experiment we suggest $\cos^2\theta$ shape of angular distribution of muons at any atmospheric level. Simulation results correspond to downward muon flux integrated over 2π at any atmospheric level produced by protons of GCRs. We multiply these data by factor 2 in order to take into account muon production by He and other nuclei species of GCRs in the atmosphere. We note that the experimental data and simulation result are nearly the same with the exception of low and high altitudes range where the accepted muons angular distribution is not valid. We plan simulate our experimental device response using GEANT4 Monte Carlo facilities.

Conclusions

We present experimental results on muon flux measurements in the atmosphere at several geomagnetic locations (geomagnetic cutoff rigidities R_c≈1-13.6 GV) obtained during the Antarctic sea expedition in November 1975–March 1976. The data on > 100 MeV muon flux absorption in the atmosphere were obtained. It allows to determine important features of atmospheric muon flux spatial distribution as follow (1) the dependence of count rate maximum of muon flux in the atmosphere on the cutoff rigidity R_c of the location can be expressed in the form $N_{max}(\mathrm{min}^{-1})= 149.12 - 48.12\,ln(R_c)$ and (2) atmospheric depth X corresponding to the maximum of muon flux in the atmosphere depends on the cutoff rigidity of the location (R_c) and can be estimated from the expression as $X(\mathrm{g}\cdot\mathrm{cm}^{-2})=9.8R_c(\mathrm{GV})+31.3$. On the other hand based on GEANT4 facilities we have calculated the secondary muon fluxes produced by GCRs in the atmosphere at several locations during solar activity minimum epoch. We found small discrepancy between experimental data and calculation results at low and high altitudes. We plan to simulate our experimental device response using the GEANT4 Monte Carlo facilities in order to determine the reason of this discrepancy.

Acknowledgments

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References

[1] S. Agostinelli, J. Allison, K. Amako, et al. Nuclear Instruments and Methods in Physics Research Section A. 506:250-303, 2003.
[2] L. Desorgher, E.O. Flückiger, M.R. Moser and R. Bütikofer. Proc. 28th ICRC. 4277-4281, 2003.
[3] L. Desorgher, E.O. Flückiger, M. Gurtner, et al., IJMPA.20:6802-6804,2005.
[4] Y. Sanuki, Y. Yamomoto, M. Motoki et al., Proc. 27th ICRC. 950-953, 2001.
[5] J.F. Krizmanic, A.J., Davis, L.M. Barbier, et al., Proc. 24th ICRC, 69-72, 1995.
[6] K.S. Hirata, K. Inoe, T. Ishida, et al., Phys Lett B280:146-152, 1992.
[7] P.N. Ageshin and T.N. Charakhchyan., Vestnik MSU, N2:77-88, 1956.
[8] V.S. Makhmutov, G.A. Bazilevskaya, L. Desorgher, E.O. Flückiger.. Izvestiya RAN, (in Russian). 69(3): 881-883, 2005.
[9] V. S. Makhmutov, G.A. Bazilevskaya, L. Desorgher, E.O. Flückiger., Adv. Space Res. 38:1642-1646, 2006.
[10] V.S. Makhmutov, L. Desorgher, G.A. Bazilevskaya, E.O. Flückiger, J.-P. Raulin., Adv. Space Res. 39:1460-1463, 2007.
[11] Galactic Cosmic Rays. Standard of USSR, N 25645.122-85, M., 31, 1986.