29th International Cosmic Ray Conference Pune (2005) **6**, 57-60

The Muon Energy Spectra at various geomagnetic latitudes

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An analysis of measurements of the muon energy spectra for different altitudes and directions performed with devices placed at various geomagnetic latitudes is presented. The idea of this report is to explore and answer the question whether the discrepancies existing among the various values are related to various geomagnetic latitudes of the device location. The charged muon ratio R (μ^+/μ^-) are discussed.

1. Introduction

Much experimental work has been done for muon fluxes in different atmospheric depths in places of a different geomagnetic rigidity cutoff. We have been gradually realizing that the muon fluxes depend also on different azimuthal angles not only on vertical ones and geomagnetic cutoff. The same is true for neutrinos. Measurements by Super-Kamiokande, IMB i MACRO have given evidence that neutrino flavor transitions exist. The interest of this research is neutrino fluxes and their angular distributions. Cosmic-ray muons and neutrinos originate from the decay of pions and kaons produced by the interactions of high-energy primary nuclei A_{cr} with atmospheric ones A_{air}.

The zenithal angular dependence of muon fluxes have been measured from the vertical direction to near-horizontal in the momentum region 0.2–5 · 104 GeV/c. Most of the experiments measured vertical muon fluxes.
Majority of the theoretical calculations of muons and neutrinos in the atmosphere has been done using the following logical schema:
The starting point is always:

1) Primary Spectrum and Primary Composition ;
2) High Energy Interaction Model;
3) Muon and Neutrino Fluxes;
4) Muon charge ratio and electron to muon neutrino ratio.

In the calculations the agreement or satisfactory agreement is quoted for the muons and is used to prove the interaction model and assumed primary spectrum. In consequence it is used to prove the neutrinos calculations.

2. The average differential muon fluxes

Available muon data allow to find the absolute average differential muon fluxes for different angles in the atmosphere [1]. Figure 1 shows an example of average vertical muon fluxes most frequently measured. Experimental data fallow the logical shape,

For the positive and negative muons we have much less available numbers of measurements and agreements between the best fit function from the fig.1 (assuming that the muon charge ratio with R=1.27) are worse(Figure 2 for positive muons).
Experimental situation is the fallowing:

1) For energy higher than about 10 GeV/c, the scatter points of experimental data are much smaller than the scatter points for law energies (below 1GeV/c).

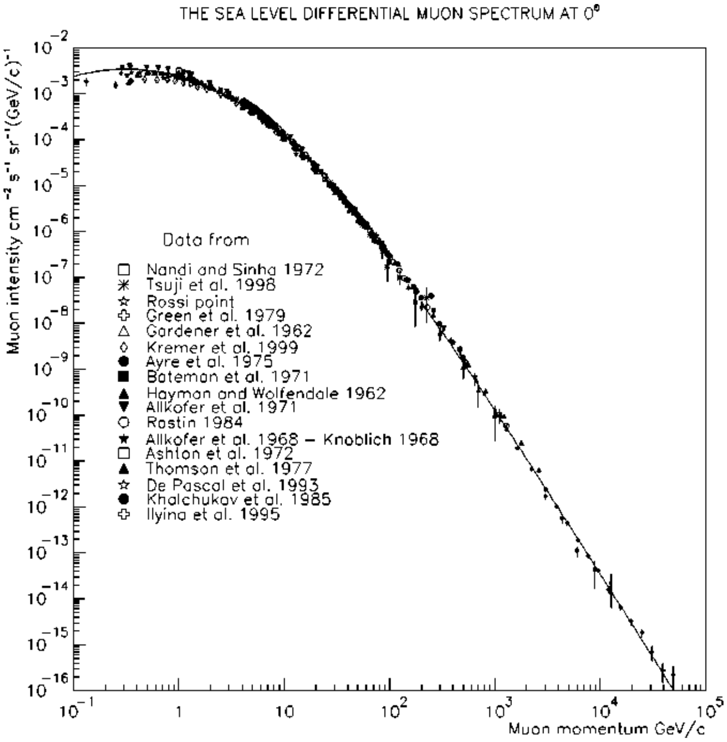

Figure 1: Average vertical muon intensities from different geomagnetic latitudes.

2) In the experiments, where the main neutrino fluxes is measured below 10 GeV/c, agreement of muon calculations for clearly higher than 10 GeV/c energies do not prove neutrino calculations for lower energies.

In the theoretical works each group has his preferable interaction model, primary spectrum and the chemical composition and his data interpretation. But the interpretations are generally compatible.

3. The zenithal angular dependence of the average differential muon fluxes

The average differential muon intensity can be expressed for low energy as $I(\Theta) = I(0) \cos^n\Theta$ where I(Θ) is the intensity at zenith angle Θ and vertical intensity of muons and n is a function of muon momentum (between n = 1.8 ÷ 5.3). For underground experiments the sec law is widely accepted.

4. The muon charge ratio

Measurements of the muon spectra at different geomagnetic latitudes aim at studies of the influence of the Earth's magnetic field on cosmic rays.

The majority of reported results of the muon charge ratio R (μ+/μ−) is in good agreement for muon energies higher than 10 GeV. The measured charge ratio (1.270 ± 0.003) seems to be well established for different muon energy threshold [2]. The excess of number of positive muons observed at sea level can be

explained not only by the fact that the primary radiation is predominantly positively charged, but mainly by preferential decay of positive pions and kaons.

The effect of the geomagnetic field on muons arriving at zenithal angle Θ at the sea level is that positive charged particles coming from the West start the flight at zenithal angles $\Theta_w < \Theta$ and negative charged particles at $\Theta_w > \Theta$.

The East-West effect was reported in papers [1] and [4]. Due to this effect the muon charge ratio $R(\mu^+/\mu^-)$ is larger in the western azimuthal direction than in the eastern.

The low values of R(μ^+/μ^-) have been reported in many papers[1] without any information about the azimuthal angular dependence for muon energies below muon momentum around 1GeV/c. The charge muon ratios R(μ^+/μ^-) are lower than 1.27. The Manchester group reported an increase of the ratio from 1.17 at p_μ = 1GeV/c to about 1.26 at p_μ = 5 GeV/c.

During the Atlantic Expedition of the German research ship Meteor the values of charge ratio: 0.98 at p_μ = 0.325 GeV/c and 1.47 at p_μ = 0.71 GeV/c have been measured.

The results of the relation between muon charge ratio and rigidity cutoff are summarized in the Table 1.

Table 1 : The collected data of the experimental results of the muon charge ratio for four different experiments and four different rigidity cutoff. Data from [1], [5], [6].

Experiment	Rigidity Cutoff GV	R(μ^+/μ^-)	Muon Energy Range MeV/c	Theory [3]
Lynn Lake Manitobu Canada	0.5	1.21±.03	200 - 500	1.20±.0.03
Fort Sumner NM, USA	4.2	1.12±.02	200 -500	1.15±.0.03
BESS-Mt.Norikura	11.2	1.04±.04	~600	-
Meteor Sea level	14.1	0.98±.13	250 -400	-

There is a clear correlation between rigidity cutoff and the muon charge ratio for relatively law muon energies below 1 GeV.

At the end of this discussion we should point out that the new data for the East West asymmetry from Hanoi experiment have been done for the highest rigidity cutoff of 17 GV [7]. The very clear azimuthal dependence of law energy muons from 120 MeV/c has been measured. These data are compatible with the earlier data of asymmetries of neutrinos [8].

There also exist the new measurements by HEAT [9] of the altitude dependence of the muon charge ratio. For a geomagnetic cutoff of 4.5 GV, the muon charge ratio does not change (is practically constant) due to the atmospheric depth. For the 1 GV cutoff the muon charge ratio seems to be higher for a small depths (below 5g per cm^2).

5. Conclusions

The conclusions of the paper are the following:

1. There are a lot of new data of muons and neutrinos that has been gathered recently from new experiments such as CAPRICE, BESS, HEAT, Super-Kamiokande.
2. It seams that we are able to understand and describe average muon fluxes in the atmosphere for the momentum higher than 10 GeV/c[1].
3. The measurements of the ratio μ^+/μ^- and $(\nu_{e+}\ \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ allows to minimize the experimental biases.
4. There is still a lot of confusion about the measuring of the moun fluxes of lower muon energies of different angles and depths in the atmosphere. There are problems with gathering the data for law

5. energy muons because the fluxes are functions of rigidity cutoff and azimuthal angles (East-West effect). The similar problem exists in measuring neutrinos.

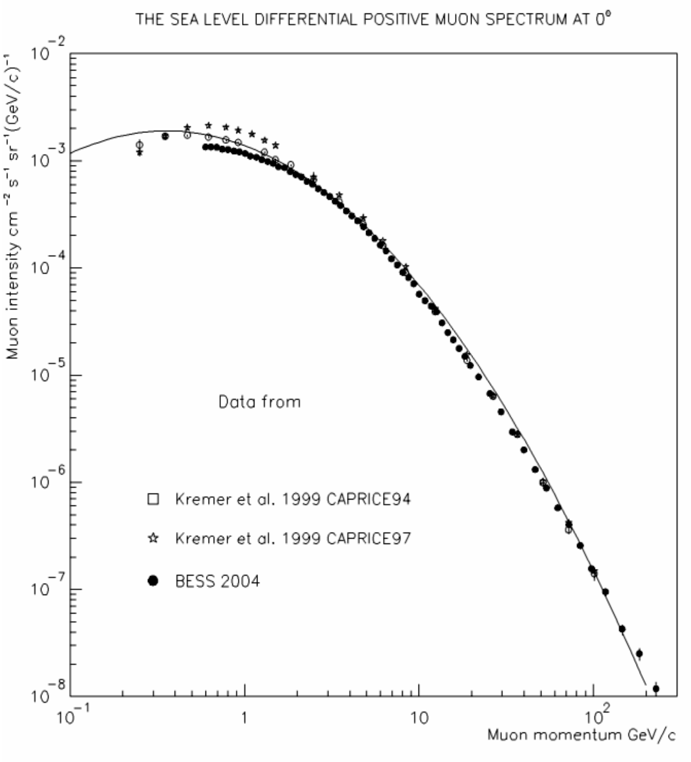

Figure 2: Average differential positive muon fluxes for the vertical direction.

6. The constancy μ^+/μ^- with the atmospheric depths shows the main role of the cascading process in the atmosphere.
7. Correlation between μ^+/μ^- values and rigidity cutoff shows that for higher rigidity the μ^+/μ^- is smaller.
8. There are differences between experimental data and different theoretical calculations. In the paper [9] we can find that law energy muon data do not agree precisely with calculations while paper [10] proves that from different models it is possible to choose one, which gives the good fit for the experimental data. In paper [4] authors state that GEISHA and VENUS do not describe μ^+/μ^- for low energies while in the paper [11], results of the GEISHA and GEANT fit experimental data.

To summarize, we need more experimental data to understand low energy muons and neutrinos data to be able to drive correct conclusions. For the theoretical calculations we need one model, which will be used for gathering all experimental data.

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