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Estimates of the Muon Signal in Giant Air Showers Induced by the Primary Photons

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The muon lateral structure functions in giant air showers induced by the primary photons have been simulated with the help of the original codes. Particularly, the density of muons with energies above 0.5 GeV at a distance of 1000 m from the shower core have been estimated for the gamma-induced showers with various energies. A comparison with the results of calculations for hadronic showers shows a considerable deficit of muons in the gamma-induced showers. The density of muons at a distance of 1000 m from the shower core happened to be ~30 times larger for the hadronic showers. Some possible constraints of the source models with ultra heavy particles and topological defects are discussed.

1. Introduction

The origin of cosmic ray particles with energies above 10^{20} eV is still an enigma. Due to the famous Greizen-Zatsepin-Kuzmin (GZK) effect [1,2] the primary protons and nuclei could not reach the Earth from distant sources. Many suggestions have been made to overcome this problem particularly with ultra heavy particles and topological defects (e.g. see [3] and reference there in). The primary gammas as a decay products of possible hypothetical objects are still an attractive variant to solve the GZK enigmas. The main problem is to be able to distinguish the gamma-induced from the proton-induced showers. The muon content and particularly the density of muons at the distance of 1000 m from the shower core have been suggested to gain success. The muon content of proton-induced showers may be estimated with help of our code MUON. As for gamma-induced showers we have developed a new code PHOTON. The cascade equations have a standard form:

$$\partial P / \partial t = -\mu_e P + S_e + \int P W_b dE' + \int \Gamma W_p dE' \tag{1}$$

$$\partial \Gamma / \partial t = -\mu_\gamma \Gamma + S_\gamma + \int P W_b dE' , \tag{2}$$

where $\Gamma(E,t)$, $P(E,t)$ – the energy spectra of photons and electrons at the depth t (in cascade units; μ_e, μ_γ – the absorption coefficients; $W_b(E',E)$, $W_p(E',E)$ – the bremsstrahlung and the pair production cross-sections; $S_e(E,t)$, $S_\gamma(E,t)$ – the source terms for electrons and photons. These equations may also be rewritten in the integral form:

$$P(E,t) = P(E,t_0]\exp(-\int_{t_0}^{t} \mu_e(E)d\xi) + \int_{t_0}^{t} d\xi \exp(-\int_{\xi}^{t} \mu_e(E)dt'(S_e(E,\xi) + A_e + B_e) \tag{3}$$

$$\Gamma(E,t) = \Gamma(E,t_0)\exp(-\mu_\gamma(E)(t-t_0)] + \int_{t_0}^{t} d\xi \exp[-\mu_\gamma(E)(t-\xi)][S_\gamma(E,\xi) + \int dE' P(E',t)W_{b\gamma}] , \tag{4}$$

where $A_e = \int P(E',\xi) W_{be}(E',E) dE'$, $B_e = \int \Gamma(E',\xi) W_p(E',E) dE'$.

At last the solution of equations can be found by the method of subsequent approximations. It is possible to take into account the Compton effect and other physical processes.

The important part is the photo-nuclear cross sections. Results would depend on possible extrapolations of this cross section into high energy region. We have used the Particle Group Data [4] and a simple linear extrapolation. As a first approximation we consider that photon interacts with a nuclei in the atmosphere as a pion and use the code MUON to estimate the muon content in the gamma-induced showers.

2. Results and discussion

Fig. 1 shows the muon lateral structure function in the primary proton induced shower with the energy of $10^{19.75}$ eV detected at the AGASA array [5]. The cosine of the zenith angle is equal to 1./1.09. The AGASA data for the same shower are shown by black squares. Dotted line is an approximation used at the AGASA array. The agreement between our results and AGASA data is good. At the distance of 1000 m from the shower core the difference is about ≈ 20%. Results of our calculations should be compared with any other simulations.

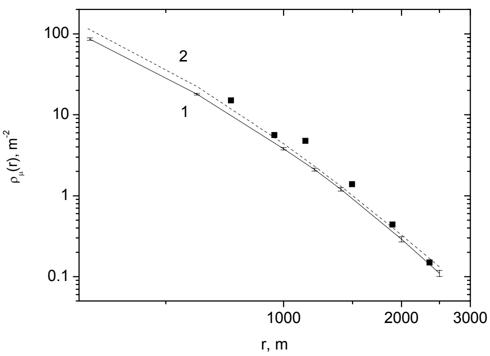

Figure 1. Lateral distributions of muons with energies above 0.5 GeV in a proton –induced shower. 1– our distribution, 2– AGASA approximation, points – AGASA data [5].

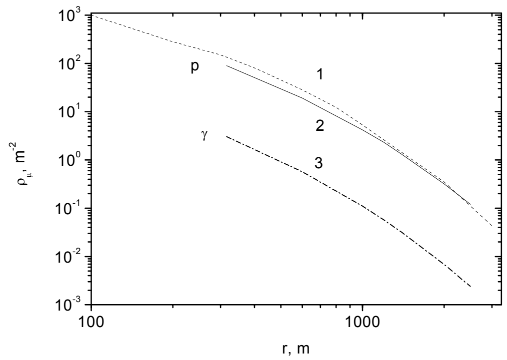

Figure 2. Lateral distribution of muons with energies above 0.3 GeV. 1– our estimation, 2 - [6], 3 – our estimation for the gamma-induced showers.

Fig. 2 shows the muon lateral distribution for the vertical primary proton with the energy of $5*10^{19}$ eV (solid curve). The muon threshold energy is equal to 0.3 GeV. Dotted curve is taken from [6]. One can see a reasonable agreement (at the distance of 1000 m the difference is about a few percent). The dash dotted curve presents the muon lateral distribution for the gamma-induced shower estimated with the help of code PHOTON. One can see that at the distance 1000 m from the shower core muon density in the gamma induced shower is roughly 40 times less than in a proton induced shower. It is very important for the problem of determination of a composition of the primary cosmic rays. To make sure that fluctuations can not contribute much to confuse a problem we carried out simulation of 10^4 proton-induced showers.

Fig. 3 shows distributions of the muon density at a distance of 1000 m from the shower core for 6 showers observed at the AGASA array. One can see that fluctuations are rather small (less than ≈10%). So it is improbable that proton-induced shower may mask the gamma showers.

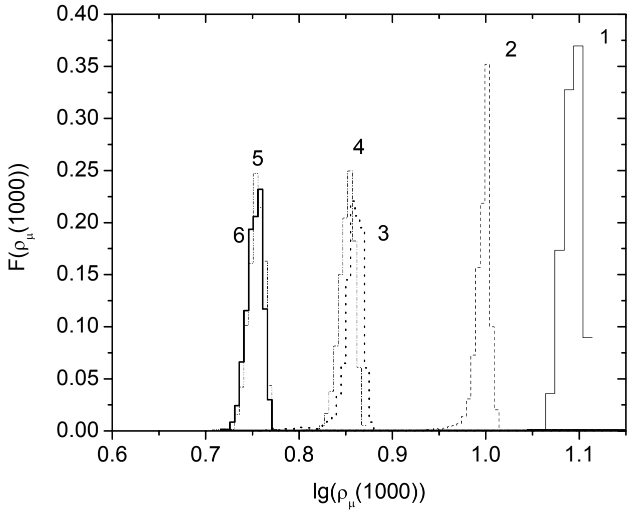

Figure 3. Distribution of muon density observed at a distance of 1000 m from the shower core.

The comparison of the muon density $\rho_\mu(1000)$ dependence on the energy of the primary particle is illustrated by the Fig. 4.

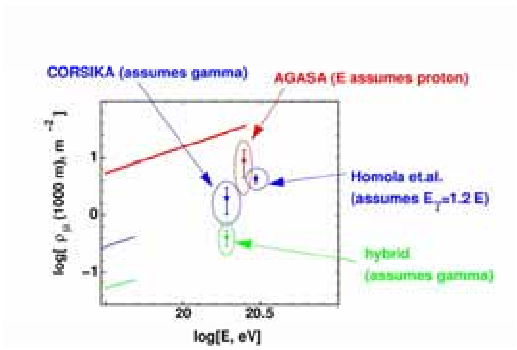

Figure 4. Dependence of muon density at a distance of 1000 m from the shower core on energy of the primary protons and gammas.

Crosses with error bars and two upper solid lines are the AGASA data and results of simulation by CORSIKA code for proton and gamma-induced showers from [7]. Circle with error bars is a result of simulations [8] for the gamma-induced showers. The lowest line is very preliminary estimated with help of our code PHOTON. It should be mentioned that low energy photons were not treated properly. Two lowest crosses with error bars are our simulations with help of CORSIKA code and a hybrid method. Our CORSIKA approach differs from the [8]: energy was not increased by a factor of 1.2 but estimated properly with the signal s(600). Besides the arrival directions were taken into account to treat a cascade in the geomagnetic field properly. The result of [9] at the energy of 10^{20} eV is nearly 10 times lower of the CORSIKA approach. First of all a large discrepancy between simulations of [8] carried out with help of the CORSIKA code and results of calculations [9] and estimated with help of our original codes is noticeable: our very preliminary results are approximately 6 times less than estimates by [8], and result of [9] is even 10 times less. Our result is higher than [9] because we disregarded the Migdal cross sections at energies above 10^{19} eV (we did not take into account the LPM effect so far). Our estimates of muon density at 1000 m from the shower core with the help of the CORSIKA code are below the results of 8]. So the main problem is to check all our codes, the code suggested by [9] in terms of the CORSIKA code. As far as constraint on the gamma-induced showers are concerned the Yakutsk data [10] should be taken into account. At least 2 showers with energies above 10^{20} eV may increase total statistic of showers up to 8 events. Our simulations with help of the CORSIKA code have been used. The standard approach to estimate probabilities have been used.Thus instead of 65% by [8] we have estimated the upper limit as 39% if data [5] are taken into account and even ~30% at the 95% CL with combined statistics (AGASA+Yakutsk data).

3. Conclusions

The very preliminary results obtained with help of original codes suggested by [9] and by us did not agree with the CORSIKA predictions for the density of muons at a distance of 1000 m from the shower axis for the gamma-induced showers. The low energy photons should be treated properly to gain agreement with the CORSIKA simulation. The crosschecking procedure should be applied to our codes. But even in the case of our CORSIKA simulations much more severe constraints such as ~30% at the 95% CL instead of 65% by [8] may be put on the models of the cosmic rays origin, such as with the topological defects (TD) or with super heavy (SH) particles.

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