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# Are deep underground detectors good $\gamma$-ray telescopes?

Todor Stanev
*Bartol Research Foundation of the Franklin Institute, University of Delaware, Newark, Delaware 19716*
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We have calculated the production of high-energy ($E_\mu > 250$ GeV) muons in $\gamma$-initiated showers. We discuss all processes which contribute to the muon production and show their yields. These yields are folded with the $\gamma$-ray flux observed from the direction of Cygnus X-3 to estimate the rate of $\gamma$-induced muons in deep-underground detectors. The fluxes of such muons are very low in magnitude, as well as in comparison with the muon background due to isotropic cosmic rays. The conclusion is that deep-underground muon detectors, even of very large area, will hardly detect any $\gamma$-induced muons.

## I. INTRODUCTION

The striking discoveries of significant flux of ultrahigh-energy $\gamma$ rays from the direction of and in phase with, several strong x-ray sources[1] not only revived interest in air-shower studies, but also inspired ideas for new detection methods. In the original Kiel observation the air showers associated with Cygnus X-3 exhibited unexpectedly large muon content.[2] This result is not yet confirmed by other groups and many recent estimates[3] showed how unlikely it is from the viewpoint of the established physics for $\gamma$ rays to generate muon-rich showers. Speculations still remain, however, that the existing and proposed very-large-area deep-underground (or underwater)[4] detectors can be used for $\gamma$-ray astronomy even if muons are rare in photon-induced air showers.

We present here a systematic calculation of the high-energy muon ($E_\mu > 0.25$ TeV) production in $\gamma$ showers taking into account all major processes. In Sec. II we briefly describe the cross sections and spectra used, the method of calculation, and show the muon yield from showers of primary-$\gamma$-ray energy $E_\gamma$ separately for each process. Section III obtains the muon rates after folding the yields with the $\gamma$-ray spectrum and discusses the energy and angular distribution of these muon fluxes. We also discuss signal-to-noise ratio in large (1000-m$^2$) underground detectors and conclude that both the low rates and weak signals make this type of observation impossible unless muons are produced in $\gamma$-ray showers through unknown channels.

## II. CALCULATION OF THE MUON YIELDS

Many processes contribute, in principle, to the muon production in photon showers. In this calculation we have separately estimated the yields due to photoproduction of pions and kaons and subsequent decay into muons, photoproduction of charm and bottom, and QED production of $\mu^+\mu^-$ pairs. The production of hadrons by the shower electrons is ineffective because of the soft spectrum of the virtual photons and is neglected here.

### A. Short description of the processes involved

We have used a photoproduction cross section, which is a parametrization of the $\gamma$-proton data converted to $\gamma$ air using $A^{0.91}$ dependence on the atomic number.[5] The cross section rises logarithmically with the incident photon energy and has a value of 2.3 mb at $10^6$ GeV. A constant diffractive cross section of 0.194 mb goes into $\rho$ production. The photoproduction interaction was assumed to be analogous to $\pi$-air inelastic interaction[6] with elasticity of 0. Because of the competition between interaction and decay the yields are sensitive to the atmospheric density and were calculated by performing Monte Carlo simulation of photoproduction events and the subsequent atmospheric cascades at a set of atmospheric depths. The yields from the diffractive $\rho$ production were followed separately, because they have somewhat different energy behavior.

The photoproduction of heavy quarks contributes significantly to the muon yields through a prompt muon production from flavored-meson decay. For charm production we have assumed for the cross section in air[7]

$$\sigma_{\gamma\text{-}c}\ (\mu\text{b}) = 4.13 \ln[E\ (\text{GeV})]\ , \tag{1}$$

which has a value of 57 $\mu$b at $10^6$ GeV. The momentum distribution of the charmed mesons is of the Weiszacker-Williams form

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{3}{2}[x^2 + (1-x)^2]\ , \tag{2}$$

and the charm-muon decay spectrum is

$$D_{c-\mu} = 2B(1-x)^2(1+2x)\ , \tag{3}$$

with a branching ratio $B = 0.1$.

The bottom-production cross section is scaled down by $(m_b/m_c)^2 = 12$, and the decay spectrum is assumed to be somewhat harder:

$$D_{b-\mu} = \tfrac{5}{3}(1-x)(1+x-\tfrac{4}{5}x^2)\ . \tag{4}$$

The QED production of $\mu^+\mu^-$ pairs is also an important prompt process for generation of high-energy muons. The energy spectrum of the muons is hard, and the cross section[8] is energy dependent before it reaches the full screening value of 12 $\mu$b at incident-$\gamma$-ray energy of around $10^6$ GeV. The production of $\pi^+\pi^-$ and higher-mass pairs is neglected not only because of the lower cross section, but mainly because the muon production is not prompt and is subject to decay-interaction competition.

 

### B. Yields per primary $\gamma$ ray

To obtain the yields per primary $\gamma$ ray we folded the differential cross sections or partial yields with the $\gamma$-ray energy spectrum in photon initiated showers. For all prompt processes the muon production does not depend on the atmospheric density, and the yield can be obtained from the equilibrium $\gamma$-ray spectrum as given by the cascade theory in approximation A (Ref. 9). The hadron photoproduction yields, however, depend on the density, and the final yields per primary $\gamma$ ray of energy $E_\gamma$ were obtained by folding the partial yields $Y_p(E, > E_\mu, X)$ with the $\gamma$-ray energy spectra $\gamma^\gamma(E_0, E, X)$ at depth $X$ in a shower of primary energy $E_\gamma$.

$$Y(E_0, > E_\mu) = \int \int Y_p(E, > E_\mu, X) \gamma^\gamma(E_0, E, X) dE\, dX \,. \tag{5}$$

Both the partial yields and the $\gamma$-ray energy spectra were calculated at 50-g cm$^{-2}$ intervals. The difference between a straightforward Monte Carlo simulation of electromagnetic cascades and the results of approximation A at these energies is small and does not change the yields by more than several percent.

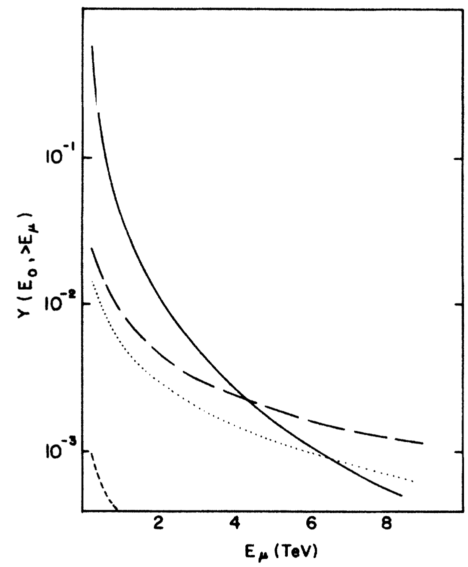


FIG. 1. Muon yields from different processes in a $10^6$-GeV $\gamma$-ray shower. Solid line, photoproduction, including diffractive $\rho$ production; long dashes, photoproduction of charm; short dashes, photoproduction of bottom; and dotted line, QED $\mu^+\mu^-$ pairs.

### C. Results

Figure 1 shows the energy spectrum of muons produced in a vertical $10^6$ shower by photoproduction (including diffractive) and the three prompt processes considered. The energy spectrum of the muons from the prompt channels roughly follow the equilibrium energy spectrum of the $\gamma$ rays in the cascade, while the decay muons have spectrum steeper by one power of $E_\mu$.

Figure 2 shows the yield of muons of energy greater than 0.5 and 2 TeV in vertical showers of $E_\gamma$ from 10 to $10^4$ TeV. Diffractive $\rho$ production is given separately. The comparison of the yields for 0.5 and 2 TeV muons illustrates the increasing importance of the prompt processes for generation of muons at higher energy. The sum of the charm and QED $\mu^+\mu^-$ pairs almost equals that of photoproduction for

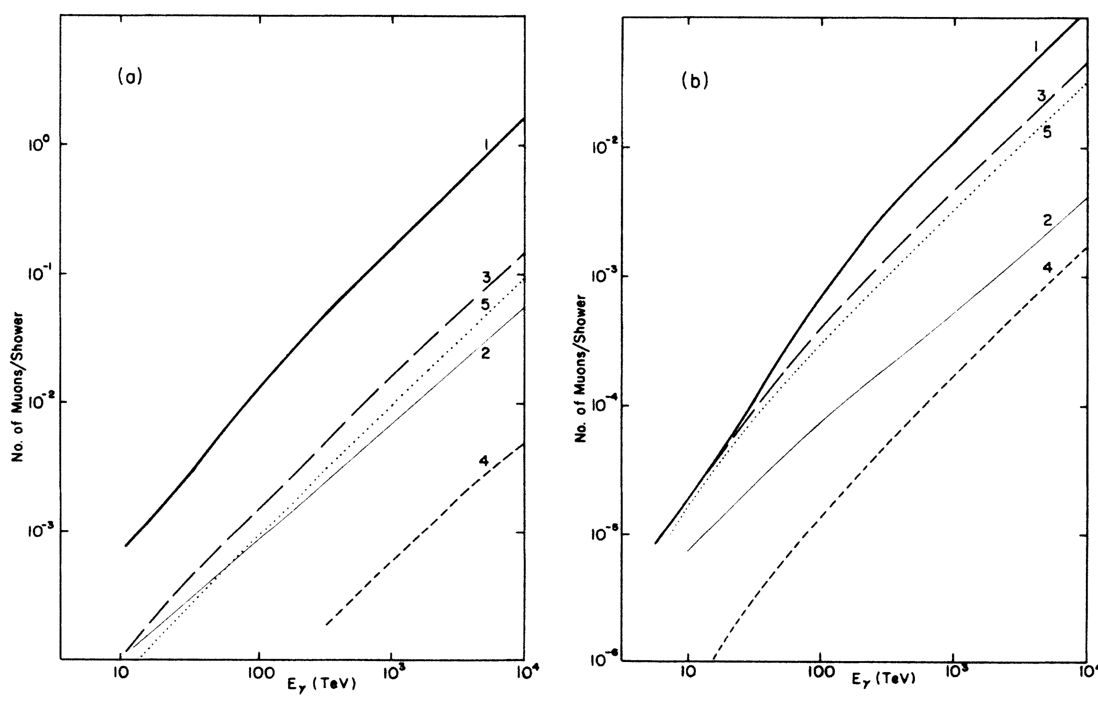


FIG. 2. Muon yields for (a) $E_\mu > 0.5$ TeV and (b) $E_\mu > 2$ TeV. Photoproduction: (1) hadrons, (2) diffractive $\rho$, (3) charm, (4) bottom. Line (5) shows the QED production of $\mu^+\mu^-$ pairs.

$E_\mu > 2$ TeV and $E_\gamma > 100$ TeV. At lower primary energies the prompt yields are even more important and dominate the production at small $E_\gamma/E_\mu$ ratio, which is crucial for very high muon energies. The production of flavors heavier than charm has a cross section too small to be important even if the decay distributions into muons are flatter, as we have assumed for bottom quarks.

## III. EXPECTED MUON RATES

To estimate the expected muon rates we have folded the yields for muons with a variety of $E_\mu$ with the primary $E_\gamma$ spectrum for the radiation from the direction of Cygnus X-3 measured by the Kiel experiment,[1]

$$N(>E_\gamma) = 6.10^{-7} E_\gamma^{-1.11} , \qquad (6)$$

where the flux is in photons $cm^{-2}\,s^{-1}$ and the $\gamma$-ray energy in GeV. We have also used a cutoff at $E_\gamma = 10^7$ GeV as suggested by the measurements of Lloyd-Evans *et al.*[1] This spectrum is higher than most other measurements, and the obtained rates have to be considered optimistic. In a typical experiment at moderate latitude the zenith angle of the source will vary from 0° to more than 90°, and the threshold energy of the detected muons will correspondingly change. On the other side, the decay muon production is higher in inclined showers. Both these factors contribute to the muon angular distribution at the detection level underground. Figure 3 shows the angular dependence of the muon fluxes in detectors at depths of 2 and 4 km of water equivalent (km we) (1 km we $= 10^5\ g\,cm^{-2}$ of rock) and flat overburden. For detectors located under a rugged terrain the angular distribution will be much more complicated and will depend on the slant depth of the rock in each direction. The angular dependence in Fig. 3 was obtained using a sec $\theta$ law for the decay muons production and the relation between depth and effective muon energy as derived in Ref. 10,

$$E_\mu = 0.53[\exp(0.4T) - 1]\ \text{TeV} , \qquad (7)$$

where the depth of the rock $T$ is given in km we.

The angular distributions thus obtained are flatter than the one for the cosmic-ray background for the following two reasons. The primary $E_\gamma$ spectrum is flatter than the background cosmic-ray one, and the contribution of the isotropic prompt muons is significant, especially for the deeper detector. The integral over the solid angles involved gives the muon fluxes at 2 and 4 km we as $4.8\times10^{-14}$ and $4.9\times10^{-15}$ muons per $cm^{-2}\,s^{-1}$. These fluxes do not account for the time the source is totally screened by the Earth and have to be additionally reduced by a factor 2 for Cygnus X-3 and latitudes of 40° N.

## IV. DISCUSSION AND CONCLUSIONS

The muon rates calculated from an optimistic $\gamma$-ray flux are very low. In a very large underground detector of an area of 1000 $m^2$ the fluxes calculated in Sec. III with account for the time when the source is shielded by the Earth will produce only seven and less than one event per year at, correspondingly, 2 and 4 km we. The crucial factor in obtaining the rates is, however, the primary-$\gamma$-ray flux. While our calculation seems to agree with other estimates[11,12] for the muon yields per primary $\gamma$ ray, the rates may differ by one order of magnitude because of the $\gamma$-ray fluxes used. Having in mind the flat primary spectrum, the cutoff at $10^7$ GeV we use here is also essential. Without the cutoff our rates at the higher end of the muon spectrum will increase by up to a factor of 2.

On the other hand, the $\gamma$-ray fluxes from far away sources are expected to be diminished in the important range of $3\times10^5$ to $5\times10^7$ GeV because of interaction on the 2.7 K blackbody radiation.[13,14] This will further decrease

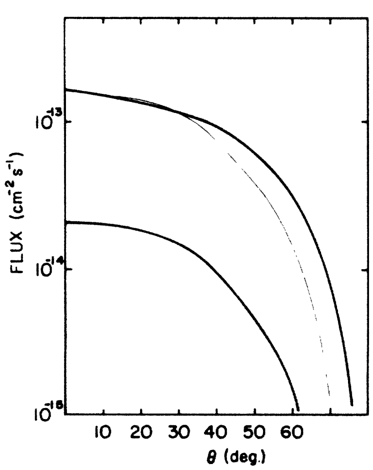


FIG. 3. Angular distribution of muons from $\gamma$ showers at depths of 2 (upper thick line) and 4 km we. The thin line shows the angular distribution of muons from cosmic-ray hadron showers, normalized to the 2-km we $\gamma$-ray line at 0°.

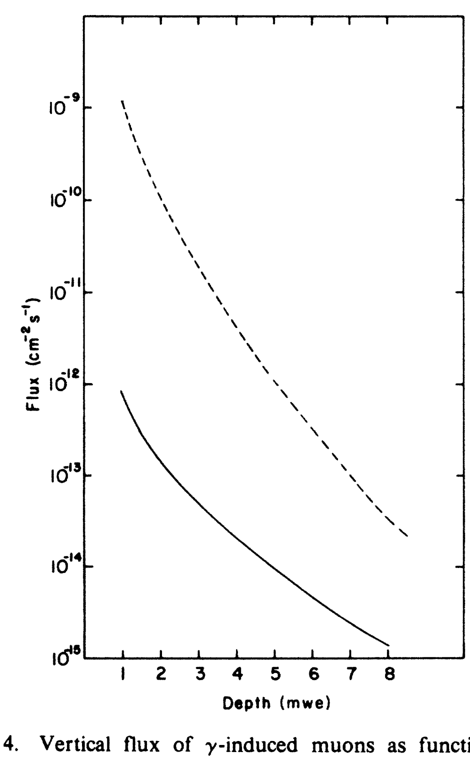


FIG. 4. Vertical flux of $\gamma$-induced muons as function of the depth compared to the cosmic-ray muon flux reported in Ref. 16.

the muon rates expected from sources at a distance greater than 10 kpc, with factors between 2 and 10 for different muon energies.

Finally, we have to compare the muon rates from $\gamma$ showers to the background cosmic-ray muons. Multiple muon scattering in the rock does not deflect deep-underground muons much from the initial shower direction,[15] and one can easily imagine underground experiment determining the muon direction with an accuracy of better than 1°. Under such circumstances the signal/noise ratio, i.e. (rate of muons from $\gamma$ showers)/(rate of background cosmic-ray muons within 1° of the source) will be 1/500 for 2 km we and 1/150 for 4 km we. The fact that the signal-to-noise ratio is much better at large zenith angles is of no consequence here because of the extremely small rates.

Figure 4 compares the vertical muon fluxes at different depths produced by the $\gamma$-ray flux of Eq. (6) with the background from hadronic showers within 1° of the source. The curve for cosmic-ray muons is based on the measurements at the Kolar Gold Fields.[16] Despite the flatter $\gamma$-ray curve, both fluxes are more than one order of magnitude apart even for a depth of 8 km we.

The overall conclusion of this calculation is that unless there are drastic changes in the interactions of high-energy $\gamma$ rays with matter, the rate of muon production in $\gamma$ showers in the atmosphere is very low. Even if the $\gamma$-ray showers become as effective in muon production as the hadronic showers, the use of underground detectors as $\gamma$-ray telescopes is not going to be an easy task.

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[1]See M. Samorski and W. Stamm, Astrophys. J. **268**, L17 (1983); and J. Lloyd-Evans *et al.*, Nature (London) **305**, 784 (1983), for observations of the ultrahigh-energy $\gamma$-ray flux from Cygnus X-3. For observations of other sources, see R. J. Protheroe, R. W. Clay, and P. R. Gerhardy, Astrophys. J. **280**, L47 (1984); R. J. Protheroe and R. W. Clay, in *Nineteenth International Cosmic Ray Conference, La Jolla, 1985, Conference Papers,* edited by F. C. Jones *et al.* (National Aeronautics and Space Administration, Washington, 1985), Vol. 1, p. 247.

[2]M. Samorski and W. Stamm, in *Eighteenth International Cosmic Ray Conference, Bangalore, India, 1983, Conference Papers,* edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 11, p. 244.

[3]See, e.g., T. Stanev, T. K. Gaisser, and F. Halzen, Phys. Rev. D **32**, 1244 (1985), and references therein.

[4]In addition to the large existing large water Cherenkov detectors of the Irvine-Michigan-Brookhaven (IMB) collaboration and Kamiokande, several very-large-area detectors are proposed for the Gran Sasso laboratory in Italy and other locations, not counting the Deep Underwater Muon and Neutrino Detector (DUMAND) project.

[5]The photoproduction cross section is discussed in more detail in Ref. 3.

[6]The interaction program used in this simulation is briefly described in T. K. Gaisser and T. Stanev, Phys. Rev. Lett. **54**, 2265 (1985). A more detailed description is in preparation.

[7]F. Halzen, K. Hikasa, and T. Stanev, University of Wisconsin Report No. MAD/PH/273, 1986 (unpublished).

[8]T. Stanev and Ch. P. Vankov, Phys. Lett. **158B**, 75 (1985).

[9]B. Rossi, *High Energy Particles* (Prentice-Hall, Englewood Cliffs, 1952).

[10]T. K. Gaisser and T. Stanev, Nucl. Instrum. Methods Phys. Res. Sect. A **235**, 183 (1985).

[11]G. Auriemma, H. Bilokon, and A. F. Grillo, Nuovo Cimento (to be published).

[12]P. G. Edwards and R. J. Protheroe, in *Nineteenth International Cosmic Ray Conference, La Jolla, 1985, Conference Papers,* edited by F. C. Jones *et al.* (National Aeronautics and Space Administration, Washington, 1985), Vol. 8, p. 318.

[13]G. Cocconi, CERN Report No. 85-021, 1985 (unpublished).

[14]T. K. Gaisser, in *Proceedings of New Particles '85, Madison, Wisconsin, 1985,* edited by V. Barger and F. Halzen (World Scientific, Singapore, 1986).

[15]T. Stanev, in *Proceedings of New Particles '85, Madison, Wisconsin, 1985* (Ref. 14).

[16]M. R. Krishnaswamy *et al.*, in *Fifthteenth International Cosmic Ray Conference, Plovdiv, Bulgaria, 1977,* edited by B. Betev (Bulgarian Academy of Sciences, Sofia, 1977), Vol. 6, p. 85.