THE MUON CONTENT OF GAMMA-RAY SHOWERS

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Abstract. We report the result of a calculation of the expected number of muons in γ-ray initiated and cosmic ray initiated air showers using a realistic model of hadronic collisions in an effort to understand the available experimental results and to assess the feasibility of using the muon content of showers as a veto to reject cosmic ray initiated showers in ultra-high energy γ-ray astronomy. We also consider the possibility of observing very-high energy γ-ray sources by detecting narrow angle anisotropies in the high energy muon background radiation.

1. *INTRODUCTION.* With the recent observation of ultra-high energy (UHE) γ-rays from Cygnus X-3 (Samorski and Stamm, 1983a; Lloyd-Evans *et al.*, 1983), Vela X-1 (Protheroe *et al.*, 1984) and LMC X-4 (Protheroe and Clay, 1985), together with the detection of excess air showers from the direction of the Crab Nebula (Dzikowski *et al.*, 1983; Boone *et al.*, 1984), it is timely to examine the muon content of extensive air showers (EAS) initiated by primary γ-rays to investigate the possibility of: (a) using a "normal" muon content to veto some fraction of cosmic ray (CR) showers; and (b) detecting γ-ray sources at very-high energies through observing narrow angle anisotropies in the muon background radiation.

Measurements of the muon content were made in two of the recent source observations, that of Cygnus X-3 by the Kiel group (Samorski and Stamm, 1983b) and that of the Crab by the Lodz group (Dzikowski *et al.*, 1983). Early predictions of muons in γ-ray EAS (Karakula and Wdowczyk, 1963; Wdowczyk, 1965; Braun and Sitte, 1965) together with later work on muons of photoproduction origin in CR EAS by McComb *et al.* (1979), had led us to expect that at 10^{15}-10^{16} eV energies γ-ray initiated EAS would have a muon content about one tenth of that of proton-initiated EAS. The ratio of muon number in the excess EAS to that in CR EAS was measured to be somewhat higher in the two recent experiments, however: about 0.6 for the observation of the Crab and about 0.7 for the Cygnus X-3 observation. This surprising result appeared to preclude the possibility of using a "normal" muon content to veto CR events in UHE γ-ray astronomy.

A number of deep underground muon detectors are now being commissioned to search for muons produced by the interaction of extraterrestrial neutrinos and an estimate of the flux and neutrino light curve for Cygnus X-3 has recently been made by Gaisser and Stanev (1985). If a significant number of muons are produceed in the atmosphere as secondaries by γ-ray showers at very-high energies, it may also be worth searching for narrow angle anisotropies in the sea-level muon background radiation as an alternative to the atmospheric Cerenkov technique. Searches of this type were conducted some years ago (Allkofer *et al.*, 1981) although not specifically for γ-ray sources.

To consider these questions we have recently performed a new calculation of the muon content of γ-ray initiated EAS using a realistic model of high energy hadronic interactions. Details of the calculation are given by Edwards *et al.* (1985).

2. *MUONS IN GAMMA-RAY SHOWERS.*

The integral energy spectra of muons we obtain at an atmospheric depth of 1130 g cm^{-2} are given in Fig. 1 for average γ-ray and proton initiated EAS for primary energies in the range 10^{11} - 10^{17} eV and 10^{15} - 10^{17} eV respectively. The atmospheric depth chosen is appropriate to the Kiel (sea level) observation of Cygnus X-3. In the Kiel and Lodz experiments, the muon measurements were obtained at fixed shower size rather than at fixed primary energy. For a realistic comparison, then, we have calculated the mean muon number for showers of given size by performing a numerical integration over primary energy taking account of fluctuations in longitudinal development. For primary CR a broken power law energy spectrum was adopted with a differential exponent of -2.7 steepening to -3.1 above 3x10^{16} eV. For γ-rays, the spectrum adopted had a differential exponent of -2 and was cut off at 10^{17} eV. The results are given in Fig. 2 and show **that the ratio of the muon number in γ-ray initiated EAS to that in proton initiated EAS is about 0.1.** If the primary composition at 10^{15} - 10^{17} eV energies is mixed or is enriched in heavy nuclei, however, the ratio would be less than 0.1. From these results then it would appear that the muon component of EAS **could usefully be employed to veto against CR initiated EAS in UHE γ-ray astronomy.**

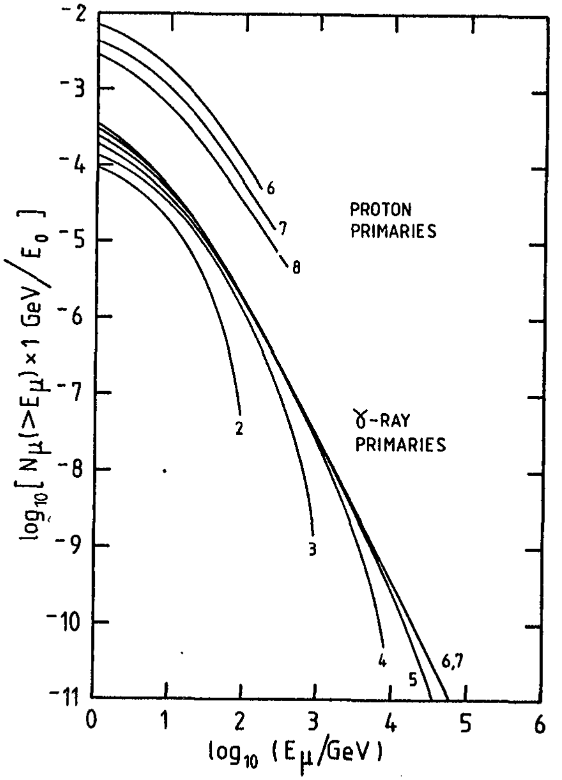

Fig. 1. Integral energy spectrum of muons in average proton and γ-ray initiated EAS divided by primary energy E_0. Numbers attached to the curves are $\log_{10}(E_0/\mathrm{GeV})$.

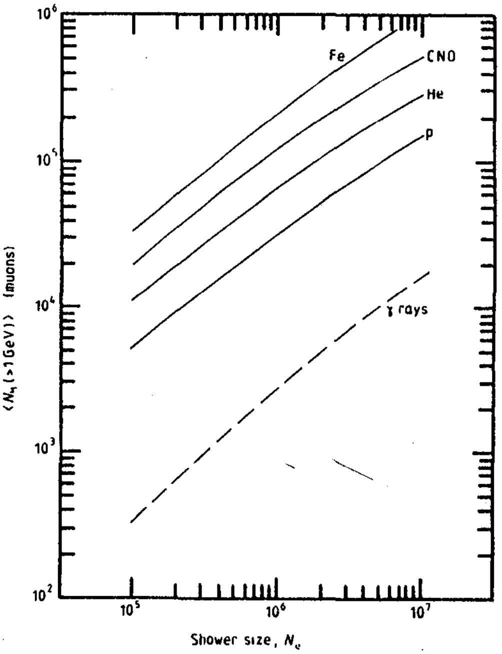

Fig. 2. Average muon number (>1 GeV) at fixed shower size at an atmospheric depth of 1130 g cm^{-2} in γ-ray and nucleus initiated EAS. (Reproduced from Edwards *et al.*, 1985).

3. *GROUND LEVEL MUON FLUX.* The flux of atmospheric muons due to γ-rays from Cygnus X-3 has been calculated by convolving the muon energy spectra in γ-ray showers (Fig. 1) with the γ-ray energy spectrum of Cygnus X-3. For this we took an E^{-2} differential photon spectrum normalised to the integral flux above 3×10^{15} eV reported by Lloyd-Evans *et al.* (1983):

$$N(E) = 4.5\times10^{-4}(E/\mathrm{GeV})^{-2} \quad (\mathrm{photons\ m^{-2}\ s^{-1}\ GeV^{-1}}). \qquad (1)$$

The resulting integral muon spectrum is shown in Fig. 3 assuming the γ-ray spectrum of equation (1) continues to a cut-off energy of: (a) 10^{16} eV; (b) 10^{17} eV; (c) 10^{18} eV. Whether this muon flux can be seen significantly above the background for a given exposure (area x time) depends on the accuracy with which the muon directions recorded reflect the γ-ray arrival directions. The angular uncertainty is likely to be made up of two parts for high energy muons: (i) uncertainty in muon track reconstruction in the detector; and (ii) angular spread due to transverse momentum imparted to parent pions. For the background muon intensity summarised by Allkofer *et al.* (1971), and assuming that γ-rays are present over 1/100th of the orbital period, the exposure required to detect muons due to γ-rays from Cygnus X-3 with 99% confidence is shown in Fig. 4 for various detector track resolutions.

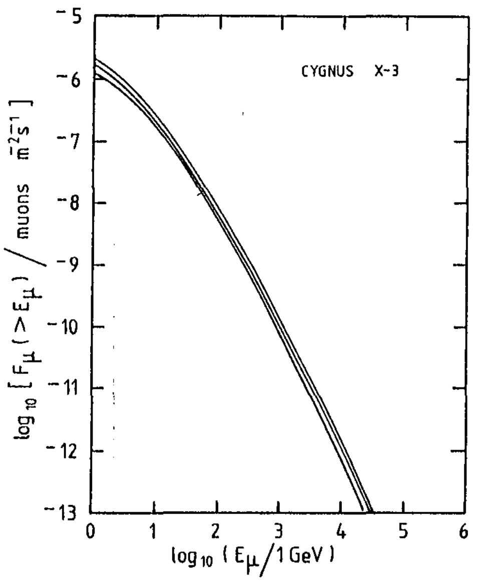

Fig. 3. Integral flux of atmospheric secondary muons due to gamma-rays from Cygnus X-3. The three curves given correspond to different assumptions about the high energy cut-off energy in the γ-ray spectrum (see text).

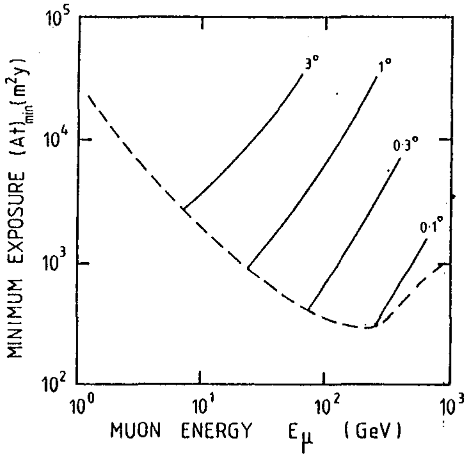

Fig. 4. Minimum exposure required as function of muon energy threshold and muon track reconstruction accuracy (the numbers attached to the curves). A lower limit is imposed by the angular spread of muons due to tranverse momentum (assumed to be: $\theta \sim \langle p_t \rangle c/E_\mu$) and by Poisson statistics and is indicated by the broken line.

4. *DISCUSSION.* From the present calculations the Kiel and Lodz results are inconsistent with the excess EAS detected by these groups being due to γ-rays. For the nearer of the two sources, the Crab, Dzikowski *et al.* (1983) have already suggested the possibility that the excess EAS are due either to neutrons

or protons, energetics arguments strongly favouring the latter alternative. The present calculations would also favour the excess EAS being due to protons or light nuclei: a ratio of 0.7 could easily be obtained if the excess events are due to protons and light nuclei from the Crab Supernova and if the galactic CR are of mixed composition at these energies (i.e. the CR's produced during the Crab supernova had a somewhat lighter composition than average). For Cygnus X-3, protons or nuclei can be ruled out because the excess EAS are observed in phase with the orbital motion of the system and it appears fairly certain that the excess EAS from Cygnus X-3 are indeed due to γ-rays. The observed ratio of muons in these EAS to that in CR EAS of 0.7 is then very difficult to explain. We conclude then that the discrepancy is likely to be due either to a systematic effect in the experiment (e.g. array triggering biasses, etc.) or alternatively, may indicate that the nature of hadronic interactions at $10^{14} - 10^{16}$ eV energies differs from our current expectations. If the first possibility turns out to be correct, then the observation of a "normal" muon content in an EAS could be used to veto CR initiated EAS in UHE γ-ray astronomy. A similar conclusion has been reached independently by Stanev *et al.* (1985).

We turn now to the possibility of observing γ-ray sources through detecting atmospheric muons. From Fig. 4 the best energy range to examine appears to be that above 100 GeV for which a detector with a 0.1° track reconstruction accuracy would require an exceptionally large exposure, in excess of 300 m^2-years when the source was in the field of view, in order to detect a significant excess from Cygnus X-3. While technically such an experiment may be feasible, there appear to be few (if any) advantages of such a system over over more conventional methods of very-high energy γ-ray astronomy (i.e. the atmospheric Cerenkov technique).

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