Gamma-ray astronomy above 50 TeV with muon-poor showers

T. K. Gaisser and Todor Stanev
Bartol Research Institute, University of Delaware, Newark, Delaware 19716

F. Halzen, W. F. Long, and E. Zas
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
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In this paper we make a quantitative evaluation of the rejection power for proton-induced showers available in principle with air-shower arrays. From a sample of more than 50 000 Monte Carlo showers we conclude that diffuse γ rays of PeV energy can be observed to a level approaching 10^{-5} of the background cosmic-ray flux by detectors sensitive to the muon component of the cascades. This may be sufficient to see the galactic disk in ultrahigh-energy photons.

I. INTRODUCTION

γ-ray astronomy is a fruitful source of information about the origin of cosmic rays and their interaction with material in the Galaxy.[1,2] The COS-*B* detector[3] and earlier experiments[4] have provided detailed maps of the galactic disk in 0.1–5-GeV photons. In addition, several point sources are clearly visible.[5] The sources of these photons include both bremsstrahlung radiation by electrons and decay of neutral pions produced when energetic ions interact with gas in the interstellar medium. It is generally believed that above several hundred MeV most of the photons originate from decay of neutral pions,[1] and that these γ rays therefore trace the ionic component of the cosmic radiation.

When the Gamma Ray Observatory and the Gamma-1 Satellite begin operation,[6] the energy range explored by instruments on spacecraft will be extended to about 30 GeV. Above these energies, for the present at least, γ-ray astronomy at higher energies must be done with ground-based detectors which can overcome the low flux of particles by virtue of their large exposure factors. The atmospheric Cherenkov technique is used in the TeV energy region[7] (VHE). At higher energies (>50 to 1000 TeV depending on the altitude of the detector) showers have enough energy to penetrate to the ground and be measured with extensive air-shower (EAS) detectors.

The ultrahigh-energy (UHE) range ($E_\gamma > 50$ TeV) is of particular interest for γ-ray astronomy because it probes parent cosmic rays with energies from ~ 500 to $>10^4$ TeV, a region in which the cosmic-ray energy spectrum steepens.[8] It is also the energy region in which a favorite scenario for the origin of cosmic rays (namely, first-order Fermi acceleration at shocks generated in the interstellar medium by supernova explosions[9]) may break down.[10] As at lower energy, both searches for point sources[11] and study of the diffuse component of UHE γ rays are of interest.

A diffuse flux of UHE photons is to be expected from the disk of the galaxy, as is observed at lower energy. On the assumption that the flux of high-energy cosmic rays elsewhere in the galactic disk is similar to what is observed in the vicinity of the solar system, it is straightforward to estimate the diffuse flux of γ rays to be expected from interactions of cosmic rays with the gas of the galactic disk. The expected level is 10^{-5} to 10^{-4} of the isotropic flux of cosmic rays of the same energy.[12]

Another source of UHE diffuse photons is the interaction of extragalactic cosmic radiation with the 2.7° background radiation if indeed the highest-energy cosmic rays are metagalactic in origin and this effect (the Greisen-Zatsepin cutoff) has removed particles originally accelerated above $\sim 10^{20}$ eV. The electromagnetic debris resulting from this interaction piles up below 100 TeV, i.e., below the threshold for $\gamma\gamma_{(2.7°)} \to e^+e^-$ pair production. A conservative estimate yields a γ-ray flux of 10^{-5} of the cosmic-ray flux.[13] Its observation would reveal similar information to the observation of the universal cutoff itself, which requires arrays of order 100 km^2. The flux would be isotropic. It is therefore in principle separable from the galactic flux of diffuse photons, which is not isotropic but reflects the concentration of interstellar matter (and possibly also of cosmic rays) in the disk of the galaxy.

Ground-based detectors look for showers generated in the atmosphere by the incident photons and therefore do not see the primary particle directly. Since showers induced by the isotropic flux of cosmic-ray protons and nuclei look very much like photon-induced showers to a ground-based detector, techniques for rejecting this hadronic background are essential. The standard technique is to look for muon-poor showers.[14,15] The purpose of this paper is to make a quantitative evaluation of the power of this technique for rejecting the hadronic background, or, in other words, to ask how frequently hadronic showers fluctuate in such a way as to have a low muon content indistinguishable from photon-induced showers. Our main result is that experiments that simultaneously observe the electron and muon components of air showers should be able to identity diffuse γ rays at a level approaching one part in 10^5 of the cosmic-ray background. Present experiments are approaching this level of sensitivity in practice.[16]

II. MUON-POOR AIR SHOWERS

In a hadronic shower muons with energies in the GeV range come primarily from decay of charged pions and kaons with $E < 100$ GeV, which usually decay before they have time to interact in the atmosphere. Photon showers, on the other hand, are primarily electromagnetic cascades, built up of pair production and bremsstrahlung. Occasionally a photon interacts hadronically, resulting in a subshower that is essentially hadronic in nature with a normal hadronic muon content. The relative probability for photoproduction (of hadrons) compared to pair production is

$$R_\gamma = \frac{\sigma(\gamma\ \text{air} \to \pi)}{\sigma(\gamma\ \text{air} \to e^+e^-)} \approx 3\times 10^{-3} \tag{1}$$

up to 150 GeV, the highest energy at which the photoproduction cross section is measured at present. As a consequence of cascading, the ratio of the average muon content of a photonic shower to that of a hadronic shower is about an order of magnitude larger than R_γ,[15] but still quite small.

The question of the muon content of photon showers has been reexamined in recent years[17,18] with results in agreement with the early calculations. The reason for renewed interest in this question is that there are surprising indications[19,20] that apparent point sources of air showers appeared to have essentially a hadronic muon content. A hadronic origin of such signals is not expected because stable, charged particles are expected to diffuse and become isotropized in galactic magnetic fields, and neutrons with energies less than 10^5-10^6 TeV do not live long enough to traverse typical galactic distances. One added difficulty with studying point sources of high-energy γ rays with ground-based detectors is that the signals appear to be sporadic. In this situation, it is particularly desirable to find a "standard candle," that is, a known source of photons that can be used for calibration. This strategy has been successfully pursued in the TeV energy range using an imaging technique to distinguish between photon- and hadron-induced showers from the Crab Nebula.[21]

Air-shower detectors measure only the size of the shower at the observation level, and there are large fluctuations from shower to shower in the relation between observed size and primary energy. For these reasons, it is important to consider shower properties classified by shower size rather than by primary energy, and to generate showers on an energy spectrum. We have generated 53 640 proton showers on an $E^{-2.7}$ differential spectrum, characteristic of the observed cosmic-ray spectrum up to > 1000 TeV. Photon showers have been generated on an $E_\gamma^{-2.0}$ differential spectrum with $E_\gamma > 100$ TeV. We have chosen this spectrum for the photons for two reasons: first, if the production of photons reflects interactions near a site of cosmic-ray acceleration, the spectrum could well be flatter than the observed spectrum; and second, use of a flat spectrum tends to overestimate the muon content of the photon spectrum because photoproduction increases somewhat at high energy. The last point means that the conclusion about the rejection power of the technique will be a conservative one.

In the simulation of the photon showers, we have used a logarithmically increasing extrapolation of the photoproduction cross section.[17] We have used the same electromagnetic cascade generator recently[22] to study the muon content of photon-induced showers in models[23] in which the photoproduction cross section is assumed to increase with energy above $E_\gamma \sim 1$ TeV. We return to a discussion of this possibility in the conclusion. Typical results are shown as a scatter plot in Fig. 1, where N_μ is the number of muons with $E_\mu > 1$ GeV. The fluctuation in the muon component of the photon showers is very large because of the competition at each stage of the shower development between the photoproduction and pair production cross sections which differ by over 2 orders of magnitude. Roughly a fraction R_γ of the showers photoproduce in the very early stage of the cascade and hence impersonate a hadron shower. The fluctuations in the proton showers are much smaller. In order to try to answer the reverse question, i.e., for what sample of cosmic-ray protons do we expect showers indistinguishable from a typical photon shower, we generated a large number of proton showers. The calculation reveals the ultimate limitation of doing astronomy by selecting muon-poor showers. It also determines the sensitivity to which one can hope to detect a diffuse γ-ray flux at PeV energies. We describe the hadron shower simulation next.

We use a Monte Carlo generator based on a particle interaction model directly tailored to high-energy accelerator data.[24] We specifically reproduce the detailed

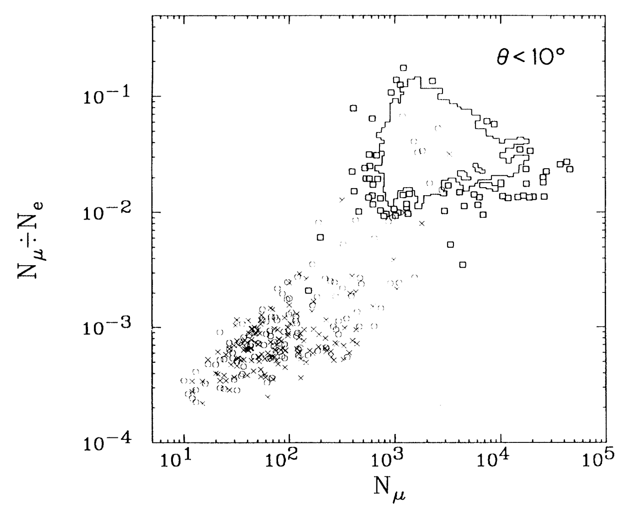

FIG. 1. Scatterplot of N_μ/N_e vs N_μ for photon (circles and crosses) and proton (squares) showers with zenith angle $\theta < 10$ degrees. The crosses (circles) differentiate simulations assuming standard (enhanced) high-energy behavior of the pion photoproduction cross section. See Ref. 22 for details. Muons are observed at an atmospheric depth of 860 g cm^{-2} above a threshold energy of 1 GeV. The bulk of the 2184 proton showers accumulates in the area delineated in the top right of the scatterplot and was omitted from the figure. The protons are generated on an $E^{-1.7}$ cosmic-ray spectrum above a threshold of 100 TeV. For the photons we assumed an E^{-1} spectrum.

features of particle production by protons on airlike nuclear targets. In order to obtain high statistics we only followed the depth development of the cascades. The program keeps track of all particles in the cascade down to 1-GeV energy. Further cascading of the electromagnetic component is done analytically using the Greisen parametrization, which is equivalent to a calculation of N_e (the total number of electrons in the shower) down to a threshold of 1 MeV, appropriate for scintillator detectors. The program also follows muon number and energy taking into account in detail μ, π, K decay, and energy loss We actually collected data, not all shown in this paper, at 700, 860, and 1013 $\mathrm{g\,cm^{-2}}$. Showers were generated up to 40° zenith angle. Muons were sampled above thresholds of 1, 2, 4, 8, and 16 GeV and the total energy carried by the muon component was recorded for each shower. Statistics of the runs are briefly summarized in Table I. A sample of the proton showers is shown in Fig. 1 for a muon energy threshold of 1 GeV and a depth of observation of 860 $\mathrm{g\,cm^{-2}}$. It can be seen that some proton showers populate the N_μ, N_e region occupied by photon showers.

III. REJECTION POWER

In this section we summarize the muon number (N_μ) distributions of photon- and proton-induced shower for two different cuts on N_e. In Fig. 2(a) we show the probability that photon and proton air cascades generate a given number of muons. The inclusive probability distribution is shown in Fig. 2(b). The showers retained for these plots have $N_e > 10^4$. For proton (photon) showers the histogram bars in the inclusive distributions represent the probability that a shower contains fewer (more) muons than the upper (lower) limit of the bin. We notice that at the one percent level the distributions overlap.

We have studied in depth the muon-poor proton showers. As expected all of them have primary energy close to the 100-TeV threshold of the simulation. In the 700-$\mathrm{g\,cm^{-2}}$ sample there are five proton showers with less than 100 muons. Two of them are the result of deep first interactions. Their muon abundance increases rapidly with depth and $N_\mu > 100$ at the next observation levels. The other three showers reach sea level with less than 100 muons and a new shower satisfied the N_μ cut at 860 $\mathrm{g\,cm^{-2}}$ as a result of muon decay and energy loss. Three of these showers have an unusually small fraction of their energy going into charged-pion production. The fourth shower has deposited a large fraction of its energy into a small number of muons. Fluctuations towards π^0-rich showers are the dominant source of muon-poor hadron showers. At depths greater than 860 $\mathrm{g\,cm^{-2}}$ very few muon-poor proton showers are due to late interactions. We have checked in general that in most of them the muons carry a low fraction of the primary energy.

The separation between photon- and proton-induced showers improves substantially when the shower size cut is increased. Such a cut should eliminate showers of low primary energy and therefore low muon number. The effect is stronger for proton showers since close to the shower maximum they have smaller sizes for the same primary energy. The cut also eliminates the occasional photon showers that photoproduce in the first interaction and as a result look like hadron showers. We have illustrated the improvements obtained with higher size cuts in

TABLE I. Statistics of our shower simulation as a function of N_e. Also listed is the average number of muons with energy in excess of 1 GeV.

	No cut	$N_e > 10^4$	$N_e > 10^5$
Sample size	53 640	32 208	2 964
Average N_μ	2 452	3 069	9 902

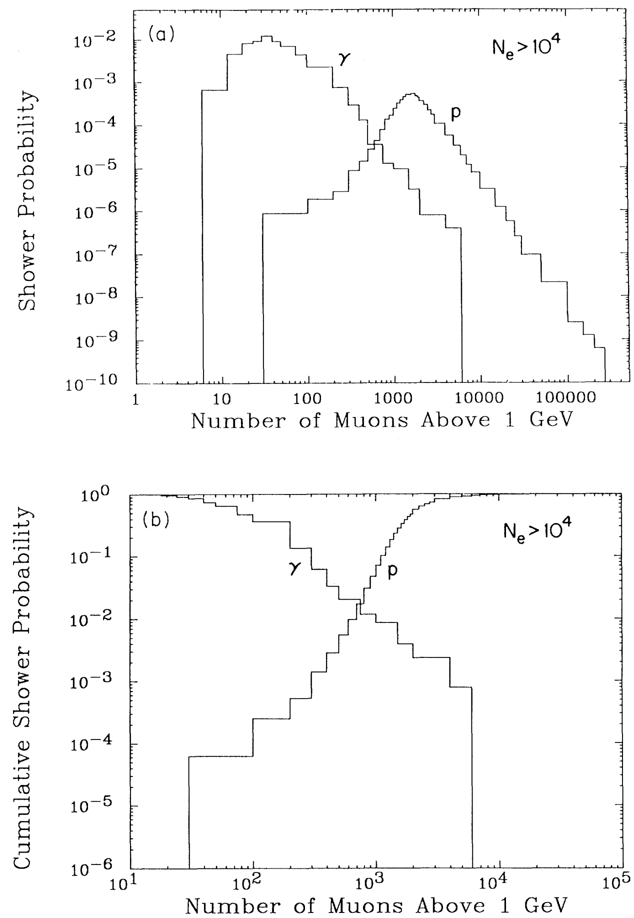

FIG. 2. (a) Probability that a photon or proton shower generates a given number of muons N_μ. The showers are those shown in Fig. 1 after a cut $N_c > 10^4$. Only the photon sample corresponding to the crosses in Fig. 1 is shown. A slow logarithmic growth with energy of the pion photoproduction cross sections measured at accelerators has been assumed in generating the muons in these photon showers (Ref. 17). (b) Inclusive probability for the histograms shown in Fig. 2(a).

Figs. 3(a) and 3(b), where we show results for $N_e > 10^5$. One can conservatively fit the proton distribution for $N_\mu \sim (1-4) \times 10^3$ and predict a proton background of 10^{-5} at $N_\mu = 100$. This parametrization overestimates the number of proton showers with $N_\mu < 1000$ in the interval where we have sufficient statistics. Refitting to all points including the $N_\mu \sim 700-1000$ region leads to a probability for proton showers to fluctuate to $N_\mu = 200$, one order of magnitude smaller, i.e., 10^{-6}. We conclude that searches for diffuse γ rays at a level of 10^{-5} should be possible after a cut in N_e. More precise conclusions are tabulated in Table II. The possibility of observing such small photon fluxes requires of course an understanding of the systematic uncertainties of the detectors at the same level.

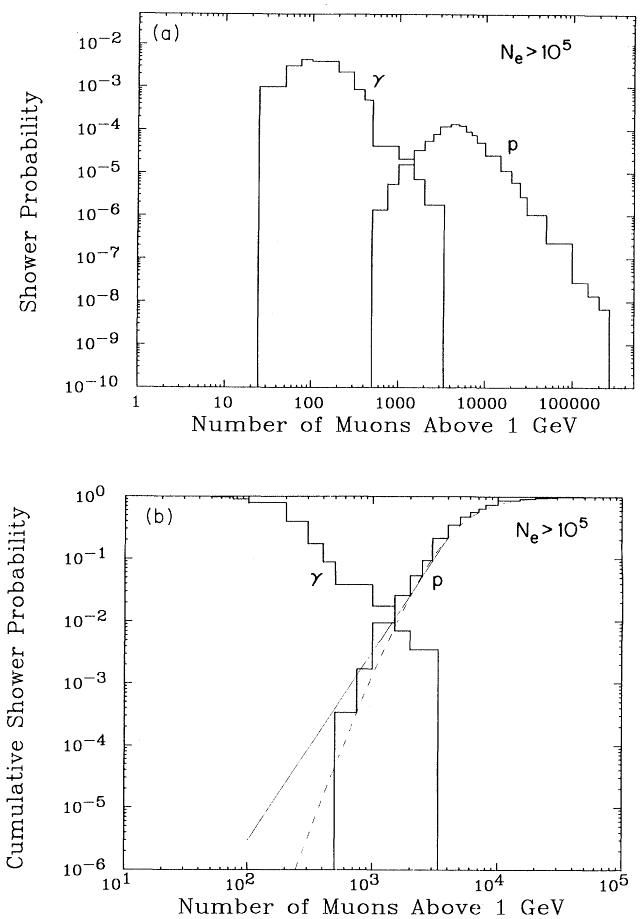

FIG. 3. Same as Fig. 2 for a cut $N_e > 10^5$.

IV. DISCUSSION

The high-energy behavior of the photoproduction cross section is determined by the gluon structure of the photon. Taking this into account one can envisage high-energy extrapolations of the Fermilab measurements leading to photoproduction cross sections in excess of those used in the conventional photon shower calculations. We generated photon showers using an extreme version of this extrapolation.[22] Some of these results are also shown in Fig. 1. The average number of muons above a GeV is increased by about a factor of 3. The small fraction of γ rays that impersonate proton showers is increased only by the amount that R_γ increases, however. This is because a photon shower has to photoproduce in the first interaction if it is to have a normal hadronic muon content. Most photon showers still have only a modest increase in the number of low-energy muons, so the effectiveness of a muon cut to remove hadronic background is little affected. An experiment observing a point source of photons can in principle measure the photoproduction cross section by studying the intermediate $N_\mu = 100-1000$ region in Fig. 1, if there is a well-established "standard candle" source of > 100-TeV photons. More direct information should be available in the near future when the hadron structure of the photon can be experimentally probed at DESY HERA, and the photoproduction cross section thus determined up to energy equivalent to $E_\gamma \sim 50$ TeV in the laboratory. This information will allow the muon-poor technique to become a more precise tool for UHE γ astronomy.

A significant fraction of the cosmic rays in this energy region could be heavy nuclei. They will yield larger numbers of muons than proton showers and we are in this

TABLE II. Implications for γ-ray detection of our calculation of the fluctuations in the number of muons N_μ for cosmic-ray showers with $N_e > 10^5$; see Fig. 3(b).

	$N_\mu < 75$	$N_\mu < 100$	$N_\mu < 200$	$N_\mu < 300$
Percentage of γ-ray signals retained	10%	20%	60%	83%
Level of cosmic-ray background				
Solid line fit	10^{-5}	1.5×10^{-5}	4×10^{-5}	10^{-4}
Dashed line fit	$< 10^{-7}$	10^{-7}	6.6×10^{-7}	4×10^{-6}

sense studying a worst-case scenario, as protons are most likely to fake γ rays. The problem of composition is of considerable astrophysical interest and our large pool of cosmic-ray showers could be helpful in deciphering the composition, e.g., for a demonstration that not all observed showers in a given experiment are protons. Our choice of an E^{-1} photon spectrum also represents a conservative scenario. Steeper spectra will indeed increase the fraction of retained high-energy γ rays in Table II.

The features of 53 640 showers have been conveniently tabulated in computer files and are available to anyone interested in the quantitative information.

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