Limits on the Isotropic Diffuse Flux of Ultrahigh Energy γ Radiation

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Diffuse ultrahigh energy γ radiation can arise from a variety of astrophysical sources, including the interaction of 10^{20} eV cosmic rays with the 2.7 K microwave background radiation or the collapse of topological defects created in the early Universe. We describe a sensitive search for diffuse γ rays at ultrahigh energies using the Chicago Air Shower Array–Michigan Muon Array experiment. An isotropic flux of radiation is not detected, and we place stringent upper limits on the fraction of the γ-ray component relative to cosmic rays ($<10^{-4}$) at energies from 5.7×10^{14} to 5.5×10^{16} eV. This result represents the first comprehensive constraint on the γ-ray flux at these energies. [S0031-9007(97)03962-8]

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We have known about the existence of ultrahigh energy ($E > 10^{14}$ eV) cosmic rays for more than 50 years [1], and yet their origin remains mysterious. Similarly, the possibility of a γ-ray component of the cosmic radiation remains an important open question in astrophysics [2]. Direct detection of ultrahigh energy photons by satellite and balloon-borne experiments is difficult because of the low fluxes. Fortunately, detection can be accomplished by large area ($>10^5$ m^2) ground-based detectors using the air shower technique. This paper reports a sensitive search for a high energy diffuse γ-ray component of the cosmic rays made by the Chicago Air Shower Array–Michigan Muon Array (CASA-MIA) experiment.

There are a variety of possible sources for a diffuse radiation at ultrahigh energies. Conventional astrophysical scenarios include (a) unresolved point sources, such as active galactic nuclei which may be the source of extremely high energy ($E > 10^{18}$ eV) cosmic rays [3], (b) decays of neutral pions produced by the collisions of cosmic rays with interstellar gas and dust [4], and (c) electromagnetic cascades resulting from the interactions of extremely high energy cosmic rays with the cosmic microwave background radiation (CMBR) [5]. In scenario (b), the diffuse γ-ray flux is expected to be concentrated in the galactic plane. We have already reported a separate search for a diffuse galactic γ-ray component [6].

In addition to these conventional sources, there might be new astrophysical or cosmological phenomena giving rise to a diffuse radiation at ultrahigh energies. For example, there is considerable speculation that the highest energy ($E > 10^{20}$ eV) cosmic rays may result from the collapse or annihilation of topological defects formed at grand unified energy scales in the early Universe [7]. With such scenarios, the production of cosmic rays is accompanied by electromagnetic cascades leading to copious γ-ray production.

In any scenario in which γ rays are produced at cosmological distances, we expect a substantial attenuation of the signal as a result of pair production with intergalactic radiation fields. γ rays near 10^{15} eV should interact with the CMBR with an attenuation length $\sim$20 kpc [8]. Nevertheless, cascading from higher energies in the presence of a weak intergalactic magnetic field can propagate γ rays over significant distances. For example, in a model which assumes an intergalactic magnetic field of 3×10^{-11} G, the expected fraction of diffuse γ rays relative to cosmic rays near 10^{15} eV is between 10^{-1}–10^{-5} for topological defects of energy 10^{23} eV created at distances out to $\sim$100 Mpc [9].

Ultrahigh energy photons and cosmic rays arrive at Earth, interact in the atmosphere, and create extensive air showers (EAS). EAS detectors sample the secondary shower particles (primarily electrons and muons). In showers initiated by cosmic-ray nuclei, muons are generated predominantly from the decays of charged mesons produced in hadronic interactions. γ-ray showers, however, are largely electromagnetic in nature since the cross section for meson photoproduction is much smaller than that for pair production, by a factor of approximately 10^{-3} [10]. As a result, we expect a much smaller fraction of secondary hadrons in γ-ray showers relative to cosmic-ray showers, and correspondingly far fewer muons. Simulations based on the MOCCA [11] and CORSIKA [12] programs indicate that γ-ray showers contain, on average, 3%–4% of the number of muons as showers initiated by protons of the same energy. These results, which agree

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with other calculations [13], are based on conventional electromagnetic and photoproduction couplings. The possibility of an anomalously high photoproduction cross section has been experimentally ruled out at HERA up to an equivalent laboratory energy of $\sim 2 \times 10^{13}$ eV [10]. The simulation cross sections are in agreement with these findings, and are assumed to continue smoothly at higher energies. The technique for distinguishing γ rays from cosmic rays by identifying muon-poor EAS was suggested more than 30 years ago [14], and its main limitation results from downward fluctuations in the muon content of hadronic showers. In all experiments prior to CASA-MIA, the muon detectors have not been sufficient in size to provide a clear statistical separation between the γ-ray and cosmic-ray regimes.

Detections of ultrahigh energy γ rays using the muon-poor air shower technique were reported in the 1960's by a Polish-French Collaboration [15] and by the BASJE Collaboration [16]. Later detections were reported by the Tien-Shan [17] and Yakutsk [18] experiments. The first significant upper limit on the diffuse photon flux at ultrahigh energies was reported by the Utah-Michigan experiment using a portion of the eventual CASA-MIA detector [19]. Upper limits have been reported by the HEGRA experiment, based on the study of the lateral distribution of Cherenkov light in EAS [20], and by the EAS-TOP detector based on muon-poor air showers [21]. The latter result used an analysis procedure in which the limit value was apparently optimized by an arbitrary cut on shower size. An upper limit based on the electromagnetic component of EAS recorded in emulsion chambers has been claimed [22], but this result is controversial [20].

The CASA-MIA experiment is located in Dugway, Utah (40.2° N, 112.8° W) and consists of a surface array of 1089 scintillation detector stations enclosing an area of 2.3×10^5 m^2, and a muon array of 1024 scintillation counters having an active area of 2500 m^2 [23]. The muon array is more than 10 times larger than any other EAS muon detector built for γ-ray astronomy. For this analysis, we use data taken between 1 January 1992 and 7 January 1996, when the full experiment was operational.

For each event recorded by CASA-MIA, we estimate the shower size from the number of *surface detector stations* struck, the shower core from the location of maximum particle density, and the shower direction from detector timing information [23]. The number of *detected muons* is determined from those muon counters hit within a narrow window (width $\sim$100 nsec) around the expected arrival time. On average, we expect 0.65 muons per event from accidental muon hits.

We have developed a set of data quality cuts, described elsewhere [24], to remove periods of time in which detector problems could potentially bias the reconstruction procedures. We require individual events to have valid information from the underground muon array, a shower core within the boundary of the surface array and at least 15 m from the edges, and a reconstructed zenith angle less than 60°. We remove events in which a mismatch was likely to have occurred between the information derived from the surface array and that derived from the muon array. The distribution of the number of detected muons in these events peaks at zero and falls rapidly with increasing muon number; 90% of the events have less than three muons. The fraction of these mismatched events is 0.034% of the total event sample, and is independent of shower size.

After all cuts, the final data sample consists of 1.370×10^9 events, which is larger by more than an order of magnitude than those used in other recent searches [19–21].

The median γ-ray energy for EAS that trigger CASA-MIA is $\sim 10^{14}$ eV. At this energy, the mean number of detected muons is $\sim$7.5, and 4.1% of the events have zero detected muons. These zero muon events result from downward statistical fluctuations in the number of detected muons in ordinary cosmic-ray EAS. To greatly improve the background rejection, we consider data samples at higher energies in which the average number of detected muons is larger. We select five nonindependent data samples by requiring the minimum number of stations struck to be greater than 50, 100, 250, 500, and 700. The total number of events, $N_{\rm tot}$, and the average number of detected muons for each sample is shown in Table I.

We use a simulation to reproduce the observed muon number distribution and to estimate the median cosmic-ray energy of each data sample, as shown in Table I. A library of artificial EAS are generated by the CORSIKA simulation code [12] using the known cosmic-ray energy spectrum (see discussion in [25]) and a chemical composition that is independent of energy and consistent with spacecraft measurements [26]. The experimental detection efficiency is determined by observing the deviation of the shower size spectrum from a power law. Using the simulated muon size and assuming a Greisen lateral distribution function [27], the number of detected muons is determined by a detector simulation which accounts for all known parameters of the muon detector (accidental muon hits, detection efficiency, etc.). We vary the median cosmic-ray energy in the simulation to obtain the best match between the simulation and data distributions of the number of detected muons. The simulation reproduces the main features of the data for all samples. There is good agreement between the cosmic-

TABLE I. Data samples used. The minimum number of stations required is listed in the first column. The total number of events, $N_{\rm tot}$, the average number of muons, $\langle N_\mu \rangle$, and the median comsic-ray energy, $E_{\rm cr}$, are given in the second, third, and fourth columns, respectively.

Sample	$N_{\rm tot}$	$\langle N_\mu \rangle$	$E_{\rm cr}$ (TeV)
>50 stations	6.9090×10^7	40.7	575
>100 stations	1.6042×10^7	78.5	1350
>250 stations	1.1863×10^6	210.6	5000
>500 stations	71 534	470.1	22 000
>700 stations	11 572	641.3	55 000

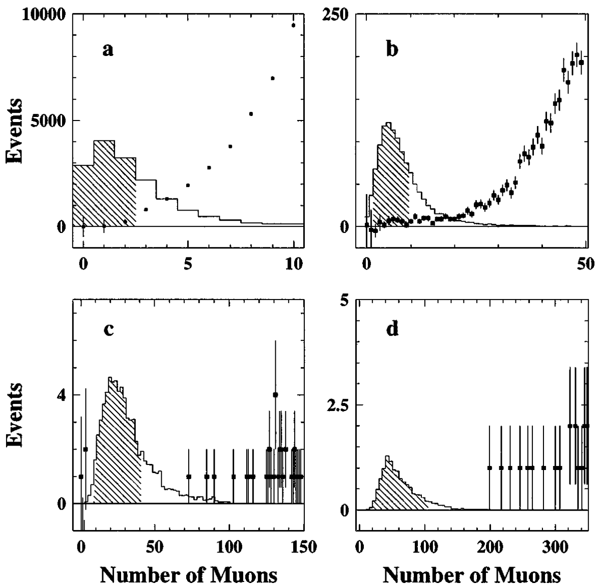

FIG. 1. Histograms of the number of detected muons for four data samples: (a) >100 stations, (b) >250 stations, (c) >500 stations, and (d) >700 stations. The data are represented by the points with error bars. The error bars account for the statistical uncertainty in the numbers of events and the systematic uncertainty in the subtraction of mismatched events. The expected γ-ray signals at a level of 10^{-3} of the cosmic-ray flux are represented by the histograms. The hatched regions correspond to the signal regions chosen to exclude known background from mistmatched events (at very low muon number) and background from ordinary cosmic-ray events (at high muon number).

ray energy values estimated from the simulation and those derived using the constant intensity method [25].

We use the simulation to estimate the number of muons expected for showers initiated by γ-ray primaries. For each sample, we define a signal region of the muon distribution in which we are confident that most of the γ-ray signal would be contained, and in which the known backgrounds are excluded. For example, in the >250, >500, and >700 station samples, we exclude the bins at very low muon content (0,1, and 2 muons) where we know there is potential background from mismatched events. Figure 1 shows the muon distributions for CASA-MIA data in comparison to the expected γ-ray distributions normalized to 10^{-3} of the cosmic-ray flux. A γ-ray signal would appear as a bump in the muon number distribution within the hatched signal regions. No significant excesses consistent with a γ-ray signal are seen in any sample. There is a hint of a possible excess of events in the >250 station sample, but it is not statistically significant. Therefore, we assume that all events within the signal regions are background and set upper limits on the γ-ray flux and on the γ-ray fraction of the cosmic rays. We estimate N_{90}, the 90% C.L. upper limit on the number of detected events, using standard statistical methods [28], and use the simulation to evaluate the efficiency for γ-ray detection, ϵ_γ, when the muon cut is applied. The upper limit on the fraction of the γ-ray integral flux relative to the cosmic-ray integral flux, $I_\gamma/I_{\rm cr}$, is given by

$$\frac{I_\gamma}{I_{\rm cr}} < \frac{N_{90}}{\epsilon_\gamma N_{\rm tot}}\left(\frac{E_{\rm cr}}{E_\gamma}\right)^\alpha, \tag{1}$$

where $E_{\rm cr}$ is the median cosmic-ray energy, E_γ is the median γ-ray energy, and α is the integral cosmic-ray spectral index ($\alpha = -1.7$, $E < 3 \times 10^{15}$ eV, and $\alpha = -2.0$, $E > 3 \times 10^{15}$ eV). The factor involving energies in Eq. (1) accounts for the fact that γ-ray primaries produce larger showers than cosmic-ray primaries of the same energy, or conversely, that γ-ray showers are detected with the same efficiency as cosmic-ray showers of higher energy. Therefore, to report a flux ratio at a fixed *cosmic-ray energy*, we correct the γ-ray flux at its energy to the higher cosmic-ray energy under the assumption that both species have the same spectral index. Table II lists the values of N_{90}, ϵ_γ, and $I_\gamma/I_{\rm cr}$ for each data sample. We use measurements of $I_{\rm cr}$ to determine upper limits on the diffuse γ-ray flux at fixed *γ-ray energies*, using the values of N_{90}, $N_{\rm tot}$, and ϵ_γ. The flux limits are given in Table II.

Figure 2 shows a compilation of measurements on the γ-ray fraction as a function of energy, including our work. The limits presented here represent the first stringent results spanning a wide range of energies, including the first results above 2×10^{15} eV. The possibility of a diffuse γ-ray flux at the 2×10^{-4} to 4×10^{-3} level, as suggested by earlier results [15–18], is ruled out. Our limits also constrain, to some extent, models [7] which invoke topological defects as the cause of cosmic radiation

TABLE II. Results of the search for diffuse ultrahigh energy γ rays. The median cosmic-ray energy, $E_{\rm cr}$, and the median γ-ray energy, E_γ, are given in the first and fifth columns, respectively, in units of TeV. The quantities N_{90} and ϵ_γ are defined in the text. $I_\gamma/I_{\rm cr}$ is the 90% C.L. upper limit on the integral γ-ray fraction, and I_γ is the 90% C.L. upper limit on the integral γ-ray flux, in units of photons cm^{-2} sec^{-1} sr^{-1}.

$E_{\rm cr}$	N_{90}	ϵ_γ	$I_\gamma/I_{\rm cr}(\times 10^{-5})$	E_γ	I_γ
575	7273.0	0.397	<10.0	330	$<1.0 \times 10^{-13}$
1350	1718.0	0.641	<6.5	775	$<2.6 \times 10^{-14}$
5000	89.5	0.663	<4.0	2450	$<2.1 \times 10^{-15}$
22 000	2.3	0.736	<1.5	13 000	$<5.4 \times 10^{-17}$
55 000	2.3	0.891	<8.0	33 000	$<5.3 \times 10^{-17}$

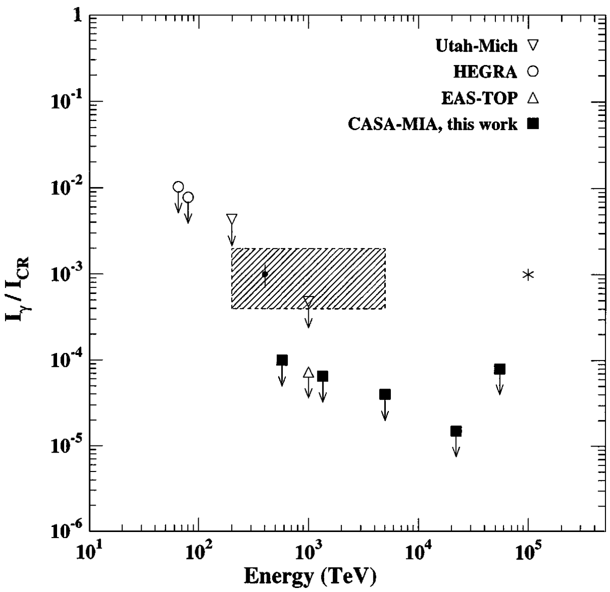

FIG. 2. Measurements of the fraction of γ rays relative to cosmic rays at ultrahigh energies. The hatched region indicates the range of γ-ray detections as reported in the literature prior to 1985 [15,16]. The results of the Tien-Shan [17] and Yakutsk [18] experiments are shown by the point with error bars and the asterisk, respectively. The points with arrows represent upper limits from the Utah-Michigan [19], HEGRA [20], and EAS-TOP [21] experiments, and this work, as indicated in the legend.

at the highest energies. The limits disfavor models which have decaying topological defects at relatively nearby distances (i.e., <100 Mpc) [9], but not those which arrange them in cosmologically uniform distributions.

In summary, based on a very large sample of air shower events whose muon content has been measured by a large muon detector, we place stringent upper limits ($<10^{-4}$) on the γ-ray fraction of the cosmic rays at energies between 5.7×10^{14} and 5.5×10^{16}. These limits rule out the possibility of a significant component of the cosmic-ray flux whose interactions are predominantly electromagnetic in nature (e.g., γ rays, electrons, positrons, etc.). In addition, by using measurements of the cosmic-ray flux, we place upper limits on the isotropic flux of γ rays at these energies, which is of fundamental astrophysical interest.

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