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Search for isotropic γ radiation in the cosmological window between 65 and 200 TeV

HEGRA Collaboration

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Abstract

Electromagnetic energy injected into the universe above a few hundred TeV is expected to pile up as γ radiation in a relatively narrow energy interval below 100 TeV due to its interaction with the 2.7°K background radiation. We present an upper limit (90% C.L.) on the ratio of primary γ to charged cosmic rays in the energy interval 65–160 TeV (80–200 TeV) of $10.3 \cdot 10^{-3}$ ($7.8 \cdot 10^{-3}$). Data from the HEGRA cosmic-ray detector complex consisting of a wide angle Čerenkov array (AIROBICC) measuring the lateral distribution of air Čerenkov light and a scintillator array, were used with a novel method to discriminate γ-ray and hadron induced air showers. If the presently unmeasured universal far infrared background radiation is not too intense, the result rules out a topological-defect origin of ultrahigh energy cosmic rays for masses of the X particle released by the defects equal to or larger than about 10^{16} GeV.

1. Introduction

While there is widespread agreement that cosmic radiation with energies above 10^{19} eV is of extragalactic origin, its sources are unknown presently [1]. One ap-

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proach to learn more about this part of the cosmic-ray spectrum, vigorously followed by various groups [1], is its direct observation with very large air-shower arrays. There is also an indirect way to obtain information on this problem, namely the observation of diffuse γ-radiation at energies between about 65 and 100 TeV [2] ("the cosmological window"). At energies above the so called Greisen cut off around $6 \cdot 10^{19}$ eV, baryons have quite a short pathlength before they suffer photonuclear reactions with the photons of the universal microwave background radiation (MBR). The produced pions decay into photons, electrons and neutrinos. Because the electromagnetic decay products themselves have a short pathlength until they undergo various reactions with the MBR (and possibly the universal radio background and intergalactic magnetic fields) [3] it is inevitable that an electromagnetic cascade develops in the universe as a result of the presence of cosmic radiation above the Greisen cut off. At energies below about 100 TeV pair production reactions with the MBR become energetically impossible and the universe suddenly gets much more transparent to γ rays than at higher energies. The products of the cascade are thus expected to pile up in a relatively narrow energy interval below 100 TeV [2]. This Letter reports about a search for this piled up γ radiation. Because no energy is actually lost in an electromagnetic cosmological cascade, the total number of photons with energies near 100 TeV is much larger than the original injected ultrahigh energy photons. These cascade products are therefore observable with relatively small arrays with a γ-hadron separation capability at these relatively low energies.

Halzen et al. [2] made the conservative assumption that the observed cosmic radiation above 10^{18} eV is universal and continues to higher energies with a power law of differential index -3. Under these assumptions the fraction f_γ of photon induced showers between 65 and 100 TeV relative to the integral background of charged cosmic-ray induced showers above 65 TeV was computed to be about 10^{-5} [2]. Wdowczyk et al. [4] got a value of $f_\gamma = 3 \cdot 10^{-5}$ under similar assumptions both in scenarios with and without an intergalactic magnetic field.

Topological defects are discussed as a source for the observed cosmic radiation above 10^{19} eV [5]. In this case the (still barely observable) radiation above 10^{20} eV exhibits a very hard spectrum with a differential index of -1.3. Aharonian et al. showed [3] that in this case f_γ could be as large as 4% because the hard spectrum injects more electromagnetic radiation into intergalactic space than the softer spectra expected for conventional theories of cosmic-ray origin. The same scenario was also studied by Chi et al. [6] with similar results.

The possibility to find direct evidence for topological defects (whose possible existence is also discussed as an explanation for the temperature fluctuations in the MBR [7]) makes a measurement of f_γ very important even if the resulting upper limit is expected to stay above the "conservative" expectation of Halzen et al. [2].

The references quoted above ignored a possible reduction of f_γ due to absorption in an universal far infrared background. Estimates of this background taking into account only the well known radiation shares from the galaxy population at cosmological distances [8,4] predict a negligible influence on f_γ. Another evaluation [9], which nearly exhausts experimental upper limits on the far infrared background radiation, could lead to a reduction in the predicted f_γ of about a factor of a hundred according to simple estimates. Definitive predictions for f_γ in various scenarios thus have to await an experimental determination of the universal far infrared background.

In the next section it is shown that no stringent experimental upper limit on f_γ has been given up to now. This analysis presents such an upper limit obtained with the air-shower array HEGRA. The discrimination of gamma-ray and hadron induced showers has been carried out by applying a novel method based on the knowledge of the lateral distribution of the Čerenkov light and the shower size N_e from charged particles at ground level. A Čerenkov detector is particularly well suited for this task because it exhibits a good energy resolution (13% for γ ray induced showers from Monte Carlo simulations) allowing to only analyze showers in the relatively narrow energy window of interest.

There are separate publications on the hardware setup of AIROBICC and its operational characteristics [10], the Monte Carlo (MC) calculations on which this letter relies [11] and the details of our γ-hadron separation method [12]. Below these subjects are only briefly summarized with an emphasis on the exact setup for the data used for the present analysis.

2. Previous limits on diffuse γ radiation between 30 and 100 TeV

There have been two previous efforts to set limits on the γ-ray background between 30 and 100 TeV. This section attempts to reinterpret these limits (which were given in more general context) as limits on f_γ. The BASJE Collaboration [13] using measurements of the muon content of airshowers on Mount Chacaltaya quotes an upper limit on the flux of γ rays relative to the hadronic background of $6 \cdot 10^{-4}$ for "energies larger than 30 TeV". By this the authors mean that the lowest energy showers in their sample have an energy of 30 TeV, their energy threshold seems to lie much higher, however. In a later publication the same group [14] retracts its earlier result pointing out that it underestimated the number of muons in γ-ray showers. Simple estimates indeed show that the cuts used in Ref. [13] are very severe and could easily cut more than 90% of the primary γ-rays.

It would be very worthwhile to reanalyze the BASJE data to obtain a limit on f_γ using advanced MC methods; at the moment no limit on f_γ can be derived from their publications.

In a recent communication He and Zhu [15] claim to set an upper limit on the fraction of γ rays relative to the cosmic-ray background of 10^{-3} in the energy range 5 TeV to 1 PeV. Their analysis is based upon published emulsion-chamber data of the flux of the electromagnetic component in the atmosphere. The authors present a simplified theoretical calculation of this flux without taking into account the chemical composition of the primary cosmic rays and find good agreement with the data thus ruling out an additional "primary" γ-ray component at the stated limit.

This method is rather indirect and it seems possible that the good agreement between data and theoretical calculation found by He and Zhu is somewhat fortuitous. The previous literature on this subject [16,17] shows a strong dependence of the calculated fluxes on fine details of the interaction model and especially on the chemical composition. The calculation of Navia et al. [17] e.g. shows a factor of 5 difference in the electromagnetic flux above 5 TeV at 100 g/cm^2 for pure protons versus a realistic chemical composition. Taking into account uncertainties in the hadronic interaction model, chemical composition, and the absolute flux of primary cosmic rays all theoretical calculations of the atmospheric electromagnetic component in this energy are bound to have systematic normalization and shape uncertainties of at least 20%. The emulsion data have similar flux uncertainties from the energy determination error alone. It therefore seems doubtful at present to constrain additional primary electromagnetic components with a comparison of data versus theory to much better than 20%.

3. Experimental setup

The data were taken with the HEGRA air-shower array at the beginning of 1993 on the Canary Island La Palma (17.7° W, 28.8° N, 2200 m a.s.l.) [18]. The array covered an area of roughly 35000 m^2 on the ground. The principal components relevant for this measurement were:

- An array of 169 plastic-scintillator detector stations with an active area of typically 0.9 m^2 each, on a grid with 15 m station distance (called "P169" below). Each station consists of a 4 cm thick plastic scintillator sheet covered with 5 mm of lead, viewed from below by two photomultiplier tubes which measure the arrival time and the number of incoming charged particles respectively.
- The AIROBICC array of 49 open photomultiplier detector stations on a 30 m grid with a photomultiplier tube (diameter 20 cm) viewing directly the night sky to detect Čerenkov light from the air shower. A mirrored Winston cone increases the light collection area and restricts the angular acceptance for showers to within about 35° from the zenith. A filter with a spectral acceptance from 300 to 470 nm above each station reduces the background from diffuse night-sky light by a factor two.

Fig. 1 shows a light disk from an air shower approaching the AIROBICC matrix on the ground. The arrival times and amplitudes of the depicted cone are measured in the 49 stations. Two χ^2-fits to the time and amplitude data are then performed to obtain information about the direction and properties of the shower, respectively.

Whenever more than 14 scintillator huts or 6 AIROBICC huts were triggered within an interval of 150 nsec and 200 nsec respectively, the amplitudes and relative times of all huts were recorded. The scintillator hut threshold was 0.3 minimum ionizing parti-

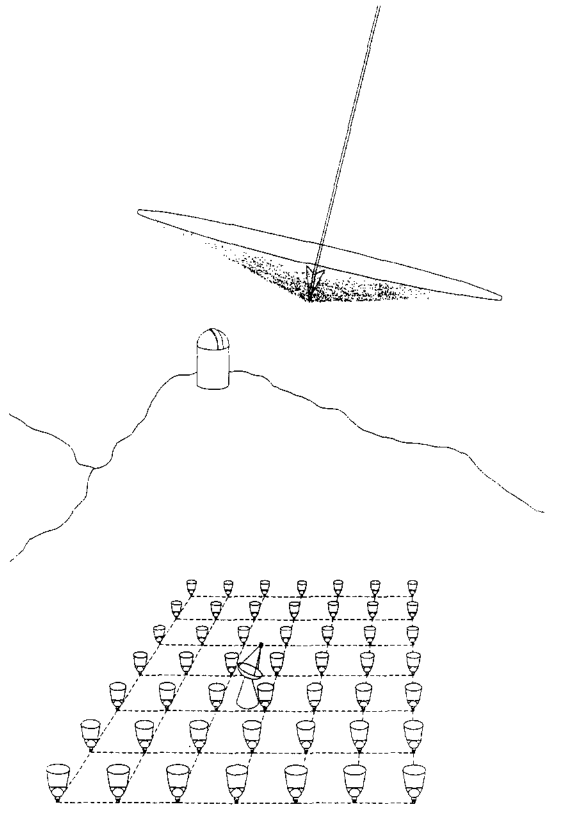

Fig. 1. Schematic picture of the light cone of an air shower approaching the AIROBICC matrix from the direction of the arrow. Near the center of the array a Čerenkov telescope is shown, which serves to check the absolute orientation of the array [10]. In the background the "Roque" mountain range is outlined with an optical telescope measuring the transparency of the atmosphere (see text).

cles equivalent, whereas the AIROBICC hut threshold (set to a level of five times the mean night-sky background fluctuation during integration time) was 4200 photons/m^2. On nights with optimal atmospheric transmission (see Section 5) these conditions correspond to an energy threshold of about 16 TeV for primary γ rays [11], and provide a raw AIROBICC trigger rate (hadron dominated) of about 14 Hz.

Only measurements larger than about 12000 photons/m^2 (the exact value varies somewhat among different stations) from the so called "low gain" channel [10] were used in the analysis of pulse heights from AIROBICC.

4. Event reconstruction

The P169 pulse height data were used to determine the shower size N_e at ground level using standard methods with some improvements [11,12] to reduce the error for small showers. Here N_e is the fitted shower size (number of particles in NKG fit), which is about 2–4 times larger than the actual number of electrons on the ground [11]. Pulse height data from AIROBICC were first normalized against each other by using the fact that stations with an equal distance from the core have to register on average the same light density.

The lateral distribution of the Čerenkov light density ρ_p as a function of the distance r to the shower core position is well approximated [10,12] by a single exponential for 10 m $< r <$ 90 m.

$$\rho_p = a \cdot \exp(-r/r_0). \tag{1}$$

Here a (in units of photons/m^2) and the "light radius" r_0 (in units of m) (which is a measure for the steepness of the lateral distribution) are free parameters. After correcting for the response function of the preamplifier, the measured AIROBICC amplitudes are proportional to ρ_p at the station position. A χ^2-fit of the experimental amplitudes in the interval 10 m $<$ $r <$ 90 m to Eq. (1) then provides estimates of r_0 and a (in amplitude units). The absolute normalization of the measured light density has been carried out by using MC data [11]. Two sets of MC showers in the energy range of this work with a zenith angle of 10 and 25 degrees respectively, and a realistic chemical composition of 70% low, 20% medium and 10% heavy primaries were subjected to the same analysis and cuts as the real data. By comparing the value of a (in photons/m^2) for MC showers with that of the real data (in amplitude units) for the same shower size N_e, it has been possible to determine the normalization factor to convert the experimental amplitude units to photons/m^2. The absolute normalization of the experimental N_e was obtained by comparing the position of the "single minimum ionizing particle (MIP) peak" [19] in the MC and experimental data. This procedure to obtain the absolute normalization of the measured photon densities is superior to a direct determination of the absolute light level, because the further analysis in Section 6 directly depends on the light/N_e ratio and systematic errors in the determination of this ratio will tend to cancel to first order.

Light intensities used in this work (namely the light density at x m distance from the shower core L_x) are always obtained by evaluating or integrating Eq. (1) with the parameters obtained from the described procedure for a given shower. They are always given in number of photons/m^2 in our spectral window.

5. Selection of data

Only the data from P169 and AIROBICC were used. A selection of optimal nights is a critical procedure for detectors analyzing Čerenkov radiation which are sensitive to changing atmospheric light transmission [10]. As expected, there is fraction of nights in which the major contributors to time variable absorption (dust and water vapor) have a negligible influence on the measurements and in which all mean parameters of the light and electron distributions are equal to within the systematic errors of about 5%. The most suited parameters for a selection are the mean of the ratio N_e/L_{90} over many showers, which is sensitive to the total absorption in the atmosphere, and the mean of the light radius which is sensitive to the differential absorption with height. We find e.g. that high cirrus leads to steeper mean light radii due to the selective absorption in the upper part of the shower development (5–10 km). Only nights which fulfilled the following conditions were chosen for further analysis:

- mean of $\log_{10}(N_e/L_{90}) < 0.3$
- mean light radius r_0 of the shower sample> 60 m

As a further independent criterion we only accepted nights in which the Carlsberg Meridian Circle (2 km away from the array) measured an extinction at a wavelength of 550 nm of $\leq 0.3^m$ (astronomical magnitudes) [20]. Data from 3.5 such nights with a total of $7 \cdot 10^5$ events in February and March 1993 were selected for the present analysis.

The following quality cuts were applied both to the real and MC data:

- $\chi^2_{\rm red} < 2$ in the fits to time and amplitude data mentioned in Section 4
- (180°-opening angle of timing cone) is in the interval 26–46 mrad
- light radius r_0 is in the interval 25–140 m
- distance of core position as determined by scintillator array and AIROBICC data respectively < 12 m
- reconstructed core position inside array and distance of the core from edge of array > 25 m

These quality cuts are useful to exclude incorrectly fitted showers, e.g. due to very large showers with their core outside the array boundaries. Such showers are not included in our MC simulation. We ensured in the MC data that the cuts do not reject photon induced showers preferentially. Only showers with more than 30 scintillator and 20 AIROBICC stations over threshold were used because for smaller showers the γ-hadron separation capability worsened considerably. A further cut on L_x was applied to restrict the energy range to the "cosmological window":

- $15000/\mathrm{m}^2 < L_{90} < 40000/\mathrm{m}^2$

The remaining showers were grouped in two zenith angle groups 0–18° (2796 showers, called M10 below) and 18–32° (3526 showers, called M25) corresponding to two MC data sets at 10 and 25 degrees [11]. The equivalent energy interval (defined as the energies where primary photons trigger the array with 50% probability) was determined from the MC data for the M10 and M25 sample as 65–160 TeV and 80–200 TeV, respectively [10]. The systematic error in this threshold determination resulting mainly from limited MC statistics is estimated to be about 5 TeV.

6. Analysis for γ/hadron ratio f_γ

Our discrimination between primary photons and hadrons [12] (the method is called "LES" for Light-Electrons-Slope) rests on the fact that on average hadronically induced showers develop slower longitudinally after their maximum, i.e. they are somewhat "longer". This leads to a ratio of particles at ground level (which measures the size of the shower at this level) to Čerenkov light L_{90} (which integrates over the shower development) which is about a factor of 1.6 smaller for photon induced showers than for hadronic showers, provided the showers have their maximum at the same atmospheric depth. In the present work we used the integral of Eq. (1) from 0–100 m L_{0-100} as a measure of total light.

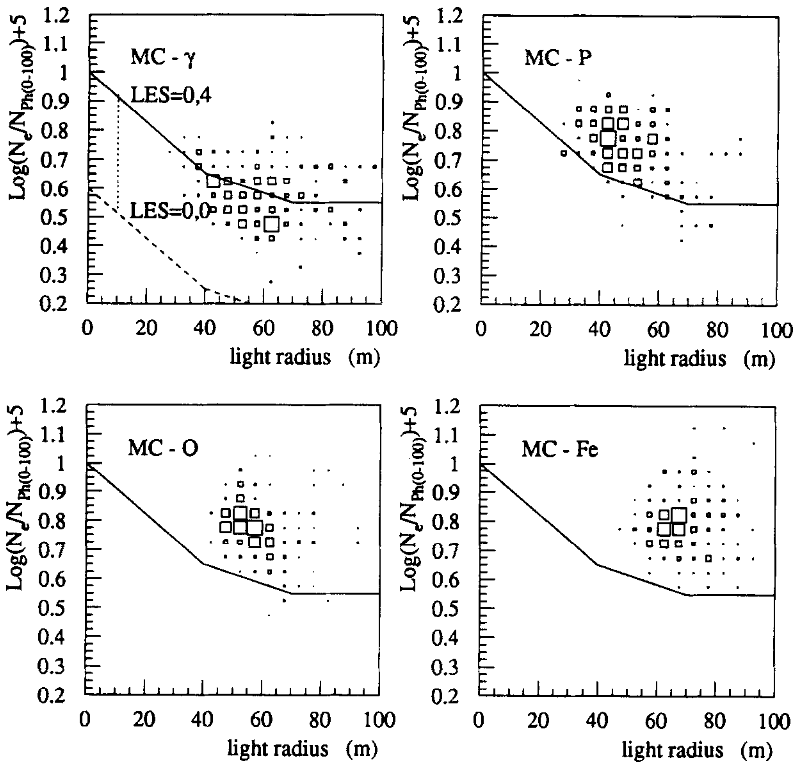

Fig. 2. Illustration of the LES method. The distribution of detector MC events in a $\log_{10}(N_e/\text{amount of light})$ versus light radius r_0 diagram for various primaries ((a) γ, (b) protons, (c) Oxygen, (d) Iron) is shown. Here and below the size of the squares is linearly proportional to the event number in the respective bin. The continuous lines correspond to LES = 0.4 in all diagrams. The dashed line labeled with 'LES = 0.0' indicates the position of the "cut line" if the value of the LES parameter is chosen as zero.

$$L_{0-100} = 2\pi \int_{0\,\mathrm{m}}^{100\,\mathrm{m}} a \exp(-r/r_0)\, r\, dr. \tag{2}$$

It was verified that virtually the same final results are obtained using L_{90} instead. The depth of the shower maximum can be shown [12] to be proportional to the light radius. In order to compare only showers with the same position of the maximum we plot the decadic logarithm of N_e/L_{0-100} against the light radius. Below a "cut line" of empirically chosen shape events are accepted as candidates for γ-ray initiated showers, above this line events are rejected as hadron initiated (Fig. 2). The cut line is shifted parallel to the ordinate by an amount parametrized by the "LES parameter" until the discrimination is optimal for a given application.

Fig. 3 shows the experimental data set M10 with a cut corresponding to LES < 0.4. Showers below the cut line corresponding to the chosen LES value of LES = 0.4 are accepted as "γ candidates". Fig. 4a shows the number of MC γ ray and hadron showers as a function of the LES parameter, Fig. 4b. is the same diagram for experimental data. This diagram was produced by shifting the cut line in Fig. 2 from a value of 0 upwards in steps of $\Delta_{\mathrm{LES}} = 0.02$ and plotting the number of events accepted as γ candidates in addition after a given step on the ordinate. Fig. 5 shows the fraction of "γ candidates" for MC γ-ray and proton, oxygen and iron induced showers as a function of the LES parameter.

There are two strategies to set an upper limit on the experimental fraction P_γ of primary γ rays in the total data sample. In method a one subtracts the expected number of background events below the LES cut line from the "γ candidates". An upper limit is calculated on the resulting number of events and this upper limit is divided by the total sample size. The highest sensi-

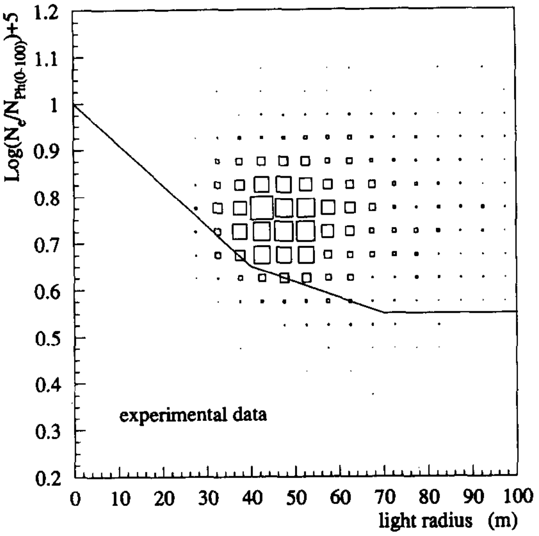

Fig. 3. LES plot of the data set M10. The number of showers as a function of light radius and the $\log_{10}(N_e/\text{amount of light})$ is displayed. The line corresponding to LES = 0.4 indicates a cut, only events below this line are accepted as γ rays.

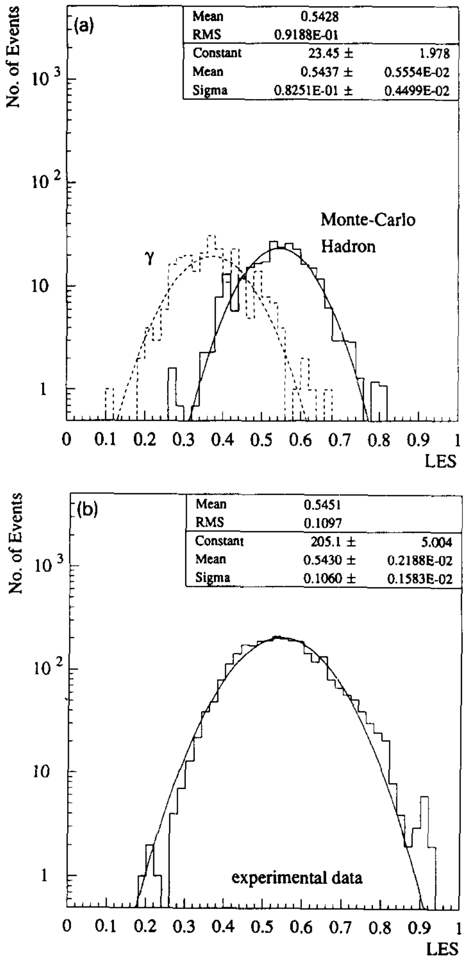

Fig. 4. (a) The number of MC events in the sample M10, as a function of LES. The continuous (dashed) line is a Gaussian fit to the hadron (γ) data. (b) The same as (a) for experimental data.

tivity of this method is reached for the "optimal" value of LES which can be shown to be the one that maximizes the "quality factor" $S_\gamma/\sqrt{S_{\text{had}}}$ in the MC data containing photons and hadrons. Here S_γ and S_{had} are the fractions of MC primary photon and hadron events respectively, which pass a given LES cut. For AIROBICC we find the best sensitivity for method a at LES < 0.4 corresponding to an accepted fraction for primary photons of about 50% (see Fig. 5). Method a is a good strategy if the number of expected background events is well known (as for example in the case of point source searches where a background region away from the source direction is chosen).

In the present analysis the background is known only from the Monte Carlo simulation however. The size of our MC library of 2400 showers [11] (the size is limited by the available computing time, the library corresponds to one year of continuous running on a dedicated DECstation) is too small to allow a statistically reliable determination of the expected background after the very restrictive cut on LES. Moreover the region of accepted showers is a very extreme one for hadronic showers (corresponding to hadronic showers which develop unusually fast) and it remains doubtful at the moment whether CORSIKA [21], the airshower simulation code used for our library, models this small "spillover" well. We therefore prefer another more conservative strategy in which the expected background is not subtracted from the event number below the LES cut line (method b). Instead all events below the cut line are considered as "γ-ray candidates". An upper limit on P_γ is derived directly on the ratio of the number of "γ candidates" to total sample size. In this case S_{had}/S_γ has to be minimized to find the optimal LES, leading to the cut LES $<$ 0.275 for our M10 data sample (see Fig. 6); this value was also used for the M25 sample.

LES < 0.275 corresponds to an accepted fraction S_γ of primary photons of only about 10% (see Table 1 for a summary of all results). We estimate the systematic error of this efficiency for the M10 (M25) sample by

Table 1
Summary of results for data sets M10 (energy range 65–160 TeV) and M25 (energy range 80–200 TeV, these results are given in brackets). The results are given both for LES < 0.4 (optimal if expected background is known, method a) and LES < 0.275 (optimal for M25 if all events passing the cuts are interpreted as signal, method b). P_γ is the fraction of events accepted as primary photons in the raw data sample after correcting for the efficiency of the LES cut.

	no cuts	LES < 0.4	LES < 0.275
γ shower (MC) (events)	249 (165)	149 (90)	22 (19)
γ shower (MC), fraction S_γ	100 (100)%	60 (54)%	8.8 (11.5)%
exp. data (events)	2796 (3526)	177 (123)	4 (5)
exp. data, fraction $S_{\rm exp}$	100 (100)%	6.3 (3.5)%	0.14 (0.14)%
$P_\gamma = S_{\rm exp}/S_\gamma$		10.5 (6.5)%	1.6 (1.3)%
upper limit on P_γ (90% C.L.)		12.7 (8.2)%	4.7 (3.3)%
upper limit on f_γ (90% C.L.)		2.8 (1.8)%	1.03 (0.78)%

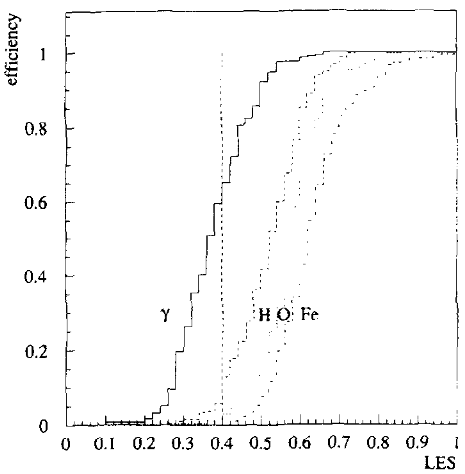

Fig. 5. Fraction of events accepted as "γ candidates" as a function of the LES parameter.

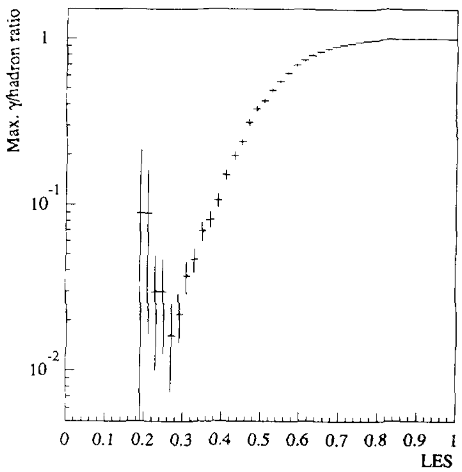

Fig. 6. Ratio of the fraction of accepted γ events to accepted hadron events in the M10 experimental data set. The minimum indicates the best possible limit on this ratio with the given set of data.

quadratically adding the statistical error of the determination (it is based on about 20 accepted MC events) and the systematic error arising from the imprecision of the MC simulation program and remaining instrumental uncertainties. To estimate the latter part of the systematic error we varied the standard deviation of the MC LES distribution for γ induced showers (Fig. 4a) by a factor equal to the ratio of the standard deviations of the experimental and LES distributions for hadron showers (Fig. 4a and 4b). The ensuing change in the accepted fraction was taken as an estimate for the systematic error of S_γ. We arrive at a total systematic error on S_γ for LES < 0.275 of about 48 (45)% for the M10 (M25) sample. The total systematic error for the LES < 0.4 cut is 8.2 (10.5)% and is dominated by the statistical part. This estimate is conservative because S_γ relies only on the electromagnetic part of our MC which is probably more reliable than its hadronic part.

Using standard techniques [22] we calculated a Poissonian upper limit on the number of "γ candidates" in the LES distribution of the experimental data. This number was conservatively increased by the systematic error and divided by the total sample size and S_γ to get an upper limit P_γ. To finally obtain an upper limit f_γ on the ratio of the total cosmic ray to the primary γ ray flux one has to divide P_γ by a factor $k = (T_h/T_\gamma)^{1.7}$ where T_h and T_γ are the energy thresholds of primary photons and hadrons according to the chosen cuts respectively. The exponent of 1.7 is determined by the spectral index of the hadronic background radiation. We determined k with the MC data to be about 3.6 for our values [23,11]. In addition we have to divide P_γ by a factor 1.3 to correct for the fact that the energy interval for hadrons is bounded at high energies, whereas f_γ is given as the ratio to the integral cosmic ray flux (remember that there is no significant flux of cosmological photons above the upper limits of the energy intervals because of the strong absorption by the MBR).

Our final results are 90% C.L. upper limits on the ratio f_γ of the primary photon flux F_γ to the total cosmic-ray flux F_{CR}:

$$f_\gamma(>80\,\mathrm{TeV}) = \frac{F_\gamma(80\,\mathrm{TeV} < E < 200\,\mathrm{TeV})}{F_{\mathrm{CR}}(E > 80\,\mathrm{TeV})}$$
$$< 7.8 \cdot 10^{-3} \quad \text{(from sample M25)}$$

$$f_\gamma(>65\,\mathrm{TeV}) = \frac{F_\gamma(65\,\mathrm{TeV} < E < 160\,\mathrm{TeV})}{F_{\mathrm{CR}}(E > 65\,\mathrm{TeV})}$$
$$< 10.3 \cdot 10^{-3} \quad \text{(from sample M10)}$$

The accepted events were scanned individually and found to have no distinctive properties except their low N_e to light ratio. Method b does not allow to positively identify whether they are primary photons or residual background.

7. Discussion

The predicted value for f_γ ($E > 65(80)$ TeV) in the topological defect scenario of Aharonian et al. [3] is 0.04 (0.025) for the case of a mass m_X of the X particles emitted by the defect of 10^{16} GeV, a factor of 4 (3.5) above the upper limits derived here. We conclude that the topological defect scenario for the origin of cosmic rays of the highest energies is seriously constrained by the present data though not ruled out due to uncertainties in the physics of topological defects and the intensity estimation of far infrared background.

Further analysis of a larger data set from HEGRA/AIROBICC will allow to improve the stated limits and go beyond the assumption of isotropy, which was implicitly used in the present analysis but might conceivably be too simple in some topological defect scenarios.

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References

[1] Proc. Workshop "Cosmic rays above 10^{19} eV" (Paris, April 1992), ed. M. Boratav, J.W. Cronin and A.A. Watson, Nucl. Phys. B (Proc. Suppl.) 28B (1992) p. 1-234.
[2] F. Halzen, R.J. Protheroe, T. Stanev and V. Vankov, Phys Rev. D 41 (1990) 342.
[3] F.A. Aharonian, P. Bhattacharjee and D.N. Schramm, Phys. Rev. D 46 (1992) 4188.
[4] J. Wdowczyk, W. Tkaczyk and A.W. Wolfendale, J. Phys. A 5 (1972) 1419.
[5] G. Sigl, D.N. Schramm and P. Bhattacharjee, Fermilab preprint, FERMILAB-Pub-94/080-A (1994), submitted to Astropart. Phys., and references therein.
[6] X. Chi, C. Dahanayake, J. Wdowczyk and A.W. Wolfendale, Astropart. Phys. 1 (1993) 239.
[7] D. Coulson, P. Ferreira, P. Graham and N. Turok, Nature 368 (1994) 27, and references therein.
[8] R.J. Gould, G. Schréder, Phys. Rev. 155 (1967) 1408.
[9] R.J. Protheroe and T. Stanev, in: Proc. Workshop "Towards a Major Atmospheric Cerenkov Detector", ed. P. Fleury and G. Vacanti (Editions Frontières, 1992) p. 103.
[10] A. Karle et al., "Design and performance of the wide angle Čerenkov array AIROBICC", Max-Planck-Institut für Physik report MPI-PhE/94-29 (1994), submitted to Nucl. Instr. and Meth A.
[11] S. Martinez et al., "Monte Carlo Simulation of the HEGRA Cosmic-Ray detector performance", Max-Planck-Institut für Physik report MPI-PhE/94-33 (1994), accepted by Nucl. Instr. and Meth. A.
[12] F. Arqueros et al., "Separation of gamma and hadron initiated air showers with energies between 20 and 500 TeV", to be submitted to Phys. Rev. D.
[13] BASJE Collaboration, K. Kamata et al., Can. J. Phys. 46 (1968) S72.
[14] BASJE Collaboration, K. Suga et al., Ap. J. 326 (1988) 1036.
[15] Y.D. He and Q.Q. Zhu, Phys. Rev. D 44 (1991) R2635.
[16] M. Shibata, Phys. Rev. D 24 (1981) 1847;
J. Bellandi et al., Prog. Theor. Phys. 83 (1990) 58;
A. Ohsawa and K. Sawayanagi, Phys. Rev. D 45 (1992) 3128.
[17] C.E. Navia et al., Phys. Rev. D 40 (1989) 2898.
[18] HEGRA Collaboration, F. Aharonian et al., in: Proceedings 23rd ICRC Calgary, Vol. 4 (Calgary, 1993) p. 291.

[19] G.W. Clark et al., Phys. Rev. 122 (1961) 637.
A.C. Smith, Nucl. Instr. and Meth. 154 (1978) 573.

[20] Carlsberg Automatic Meridian Circle, Meteorological data January–June 1993, Copenhagen-Royal Greenwich-Armada Observatory Report (1994), unpublished.

[21] J.N. Capdevielle et al., Kernforschungszentrum Karlsruhe Report KfK 4998 (1992), unpublished.

[22] O. Helene, Nucl. Instr. and Meth. 212 (1983) 319.

[23] A. Karle, PhD thesis, University of Munich (1994), Max-Planck-Institut für Physik report MPI-PhE/94-17 (1994), unpublished.