A search for diffuse emission of UHE gamma rays in southern sky from observation of hadronless air showers

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(Submitted 15 February 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **57**, No. 6, 323–329 (25 March 1993)

The lateral distributions of hadrons in air showers have been determined precisely as a function of the core distance, the shower size, the zenith angle and age, and the hadronless showers as candidates of gamma-ray-initiated air showers can be discriminated with this average lateral distribution. There is no evidence of the detection of gamma rays from any diffused regions with enough significance, but the arrival directions of hadronless air showers selected under strict conditions have an anisotropy in the equatorial coordinates.

Introduction. Study of diffuse gamma rays has attracted considerable attention. The galactic plane has been recognized as a possible region for the detection of diffuse gamma rays in the energy region between 100 MeV and 10 TeV.[1–6] In the energy region above 100 TeV, Nikolsky *et al.*[7] reported the detection of diffuse gamma rays as the flux of $(3.4\pm1.1)\times10^{-13}$ $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$ at energies greater than 4×10^{14} eV. They pointed out that this flux was concentrated at a higher galactic latitude. Also Berezinsky *et al.*[8] suggested that the expected integral flux of diffuse gamma rays from the galactic center with energies greater than 10^{14} eV would be 6.6×10^{-13} $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$. The Lodz group[9] reported a small excess ($1\sim2\%$) of muonless air showers with energies above 10^{16} eV from the direction of the galactic plane, but they observed no significant excess in the energy region below 10^{16} eV. An anisotropy of cosmic rays above 10^{14} eV was reported by Wdowczyk *et al.*[10] They suggested that the excess of air showers from the direction of the galactic center exists in the energy region of $10^{14}\sim10^{16}$ eV. They concluded that gamma rays would play a key role in explaining this anisotropy.

At energies below 10^{15} eV an effective reduction, rather than an increase, of hadronic air shower collecting area is required. For this purpose it is important to take into account the difference between the gamma-ray-initiated showers and proton/nucleus showers. Recent calculations[11,12] have indicated that the muon component represents 10% of the proton-initiated air shower, and even a much lower amount compared with heavy-nucleus-initiated air shower. However, muon discrimination of gamma-ray-initiated air showers is not effective because of its wider geometrical spread in the air shower, and because of the small number of muons in this energy region. With the same interaction background, a small hadronic component is also expected to be in the gamma-ray air shower.[13] A hadronic component concentrates in a rather small area near the core with a steep lateral distribution, so that this can provide a good measurement of hadron content in air showers, with less ambiguity due to the particle sampling effect, as compared with a measurement of the muon component. In addition, at a high altitude (5200 m), at which air shower development reaches it maximum stage, it would be possible to observe showers initiated with lower gamma-ray energies. Observation of UHE gamma rays with a hadron discrimination is the most suitable way because of the abundant hadron component in its development stage at 5200 m.

Experimental. Observation of UHE gamma rays with energies greater than 6×10^{13} eV has been carried out at Mt. Chacaltaya ($S16°21'$ $W68°08'$ and 5200 m a.s.l.) with an SYS air shower array since February 1986 (Ref. 14), with close attention focused on the hadronless air showers. The air shower array consisted of thirty-one 0.25 m^2 and four 1.0 m^2 scintillation detectors for density measurement of air showers. Air shower parameters, the electron size (Ne), the shower age (s), and the core location are determined from these local densities of each detector. Five 0.25-m^2 fast timing (FT) detectors were located at the corners of a pyramid with a base of 12 m and a height of 4 m in the center of the air shower array, for determination of the arrival direction of an individual air shower. In October 1987, three 0.25-m^2 FT detectors and five density detectors were installed in order to improve the accuracies of each air shower parameter.

The hadronic component in the shower core can be detected with an 8-m^2 hadron detector, which consists of thirty-two 0.25-m^2 scintillation detectors (burst detectors) covered with a 15-cm-thick lead absorber. These counters are used for detecting the bursts produced in the lead absorber by hadrons. The burst size (the number of burst particles) is considered as the quantity proportional to the energy flow of the hadronic component in a detector. In this experiment, a threshold level of burst size for a burst detector is set to be 5 particles (corresponding to a hadron energy of about 10 GeV).

Analyses of Hadronless Air Showers. The analyses of showers were taken from October 1987 to April 1990. The accuracy of Ne was estimated to be $\pm50\%$ and $\pm30\%$ for showers with energies of 10^{14} eV and greater than 10^{15} eV, respectively. The position of the air shower core was determined with an accuracy of ±0.5 m for a shower with an energy greater than 10^{14} eV and with the core location within a radius of 20 m from the hadron detector. The arrival directions of individual air showers were determined by the fast-timing method. The ambiguity of determination of the arrival direction was estimated by a simulation method. The uncertainties in the arrival direction were evaluated with the angle of the difference between the true and the simulated angle, in which $>90\%$ of the simulated air showers were contained. The values of ±3.5 and $\pm2.2°$ were obtained for air showers with Ne of $10^{4.8}$ and $10^{6.0}$, respectively, for this experiment.

The number of hadrons in the 8-m^2 hadron detector can be estimated from the number of detectors that detect hadronic bursts, of the thirty-two burst detectors.

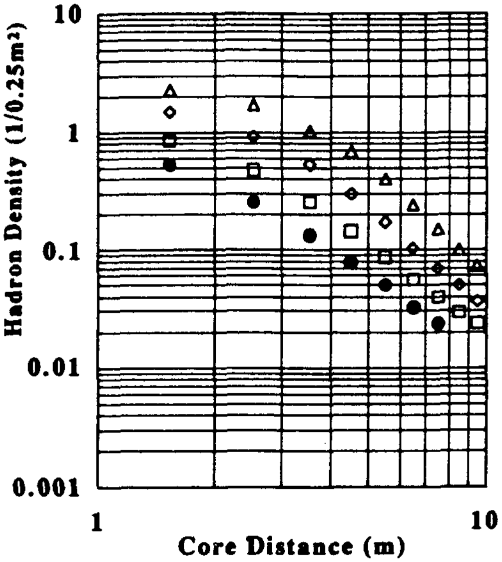

FIG. 1. Lateral distributions of hadrons for showers with sec $\theta < 1.2$ and $s=0.7$–1.5. Their distributions are shown in different Ne regions: $10^{4.8}$–$10^{5.0}$ (●), $10^{5.0}$–$10^{5.2}$ (□), $10^{5.2}$–$10^{5.4}$ (○), $10^{5.4}$–$10^{5.6}$ (△).

Hadronless air showers should be selected by the quantitative parameter (here we used R_H) as a criterion compared with the average content of the hadron component in general air showers. For this purpose, reliable lateral distributions of hadrons as a function of Ne, θ, s and core distance for general air showers are required.

This hadron detector consists of 32 burst detectors, so we treat it as independent groups of burst detectors located at the same core distance band with a width of 1 m (here the number of detectors in the group is T). When Δ is the hadron density per detector in a certain core distance band, the probability $P(\Delta, n, m)$, where n is the number of detectors detecting the hadronic burst and the remaining m $(T-n)$ do not detect, is determined by a statistical method:

$$P(\Delta,n,m)=\frac{(m+n)!}{m!\,n!}(e^{-\Delta})^m(l-e^{-\Delta})^n.$$

For a given combination of n and m, the most probable density, Δ_0, can be calculated from the value of the maximum of $P(\Delta, n, m)$. We then have

$$\Delta_0=\ln\frac{m+n}{m}.$$

For the extreme cases, i.e., $m=0$, the hadron density is assumed to be the density for $P(\Delta, T, 0)=0.5$. Inside each core distance band, there must be at least five detectors (T) for the determination of Δ_0 in this analysis.

The average lateral distributions of hadrons for the four different size regions (Ne: $10^{4.8}\sim10^{5.6}$ in every 0.2 logarithmic bins), the age value of $0.7\sim1.5$, and sec $\theta\leqslant1.2$ are shown in Fig. 1. The best function which we have found to fit these lateral distributions is

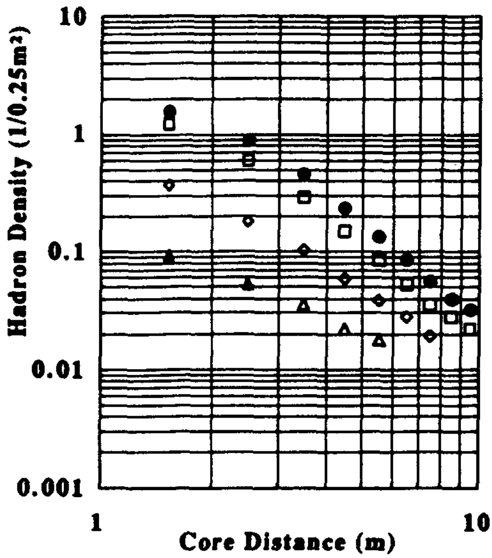

FIG. 2. Lateral distributions of hadrons for showers with $Ne=10^{5.0}$–$10^{5.2}$ and sec $\theta\leqslant 1.2$. They are shown for different s values: 0.7–0.9 (●), 0.9–1.1 (□), 1.1–1.3 (○), 1.3–1.5 (△).

$$\rho(Ne,R,\theta)=A(\theta)B(Ne)\left(\frac{R}{R_m}\right)^{-\alpha}\left(1+\frac{R}{R_m}\right)^{-\beta},$$

$$A(\theta)=0.5609\times 10^{0.01140\theta}.$$

The lateral distributions of hadrons for different values of s are shown in Fig. 2. The absolute number of hadrons at a certain core distance depends strongly on s in the fixed Ne region. The shape of the electron lateral distribution derived from the NKG function is related to s in the smaller core distance region. The parameter s is considered the stage of the air shower development; namely, the air shower with a large age has been already developed and one with a small age is the stage of development at the observation level. The number of hadrons correlates closely with the air shower development because a hadron is still the energetic component in air shower, especially at the level of Chacaltaya. From a better correlation between s and the number of hadrons, s can be taken into account independently with hadronless air showers for the effective rejection of proton/nucleus initiated air showers.

For the analysis of hadronless air shower we assume that the cross section of the photopionization does not increase, which strongly increases the energy of a photon; i.e., the number of hadrons resulting from a gamma-ray initiated shower is much smaller than the number of hadrons from a hadron/nucleus initiated shower at a comparable energy. When the shower s i different core distance bands inside hadron detector, values of density $\rho^i_{\rm obs}$, respectively, are calculated. To preserve the dynamic range of the available hadron density for hadronless air showers, we have defined an "effective core distance" region for each Ne bin. At each core distance band, the individual ratio R_j to the expected hadron density $\rho^i_{\rm exp}$, derived from the lateral function mentioned above, are defined by the quantity

$$R_j = \frac{\rho^{j}_{\text{obs}}}{\rho^{j}_{\text{exp}}}, \quad j = 1,2,...,i.$$

The degree of hadronless air shower is estimated, after taking an average, as follows:

$$R_H = \langle R_j \rangle, \quad j = 1,2,...,i, \quad R_H(\%) = R_H \cdot 100.$$

Results and Discussions. For analysis of the contour map which shows the excess region of hadronless air showers we divided the sky into 1710 spaced directions [$4° \times 4°$ square bins in right ascension (α) and declination (δ)] that cover the sky in a declination band from $-54°$ to $+22°$. The excess in each bin above the expected background is determined with the statistics of Li and Ma.[15]

Analysis was carried out for showers with Ne greater than $10^{4.8}$ and θ less than 35°. Analysis was also made for hadronless air showers with $R_H(\%) = 30\%$ and an s value of $1.1 \sim 1.5$, which are expected as developed air showers (which start their development, at a higher altitude). Consequently, 37027 showers (11%) were selected with these conditions. Contour map of excess in equatorial coordinates is shown in Fig. 3a with the position of the galactic plane, and sigma distribution is also shown in Fig. 3b for this contour map. The contour lines of sigma greater than 1.0 are drawn at every 0.5 and the regions with sigma > 2.0 are shown with black areas in the figure. No significant anisotropy in any positions of several potential x-ray binary objects, galactic center, galactic plane, and supernova remnant LOOP I could be found. The distribution of sigma is almost consistent with the one expected from the statistical fluctuation. An upper limit of intensity for hadronless air showers ($E > 2.1 \times 10^{14}$ eV) is estimated to be $(6.18 \pm 3.1) \times 10^{-12}\ \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ with 90% C.L.

The strictest selection of hadronless air showers was made with an attempt to regulate showers detecting no burst particles in any burst detectors, in spite of the fact that their core locations were inside an area of the hadron detector. In general, many hadrons remain in a region within 1 m from the air shower core, especially at a high mountain altitude. We selected air showers without any signals from thirty-two burst detectors, under conditions with Ne greater than $10^{4.6}$, s of $0.7 \sim 1.5$, and $\sec\theta < 1.2$. As a result, 291 showers could be selected with these conditions from a total of 22283 showers with core locations inside an area of hadron detector. Moreover, 99 showers whose core locations are within 1 m from the center of the hadron detector are selected from these 291 showers, in an attempt to reduce effects due to an ambiguity of the determination of the core locations. However, it is possible that some background proton/nucleus initiated air showers with smaller Ne may still remain in such selected showers, as a result of large fluctuations of a small hadron density. Therefore, Ne regulation of greater than $10^{5.0}$ is applied for emphasizing the peculiarity of a number of hadrons, and the distribution of the arrival directions for selected 29 showers in equatorial coordinates is obtained, as shown in Fig. 4. In the figure, the arrival directions of showers with $Ne > 1.5 \times 10^{5.0}$ are shown with large closed circles. Such hadronless air showers are distributed in a rather larger declination region in the range α of $10° \sim 130°$; on the other hand, in a smaller declination region they are distributed in the range α of $200° \sim 330°$. Furthermore, an apparent concentration of showers with

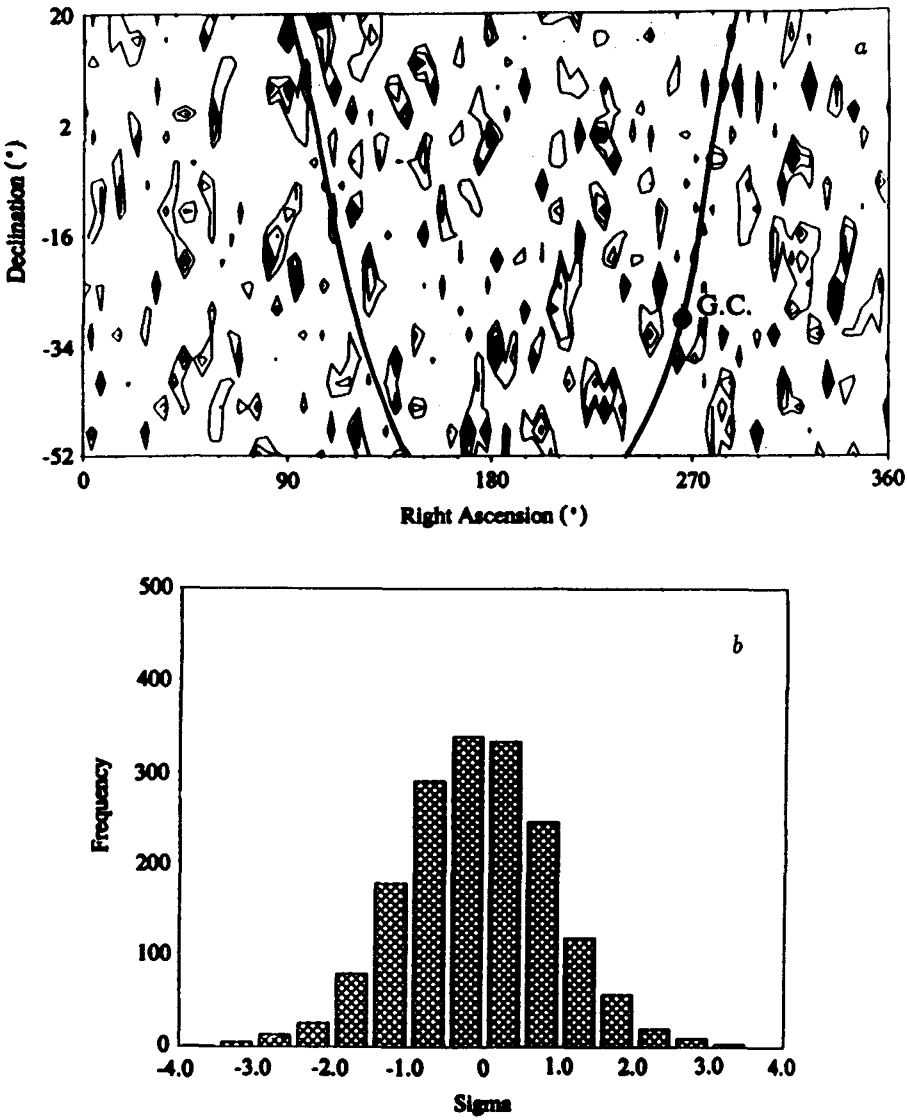

FIG. 3. (a) Contour map of excess for hadronless air showers ($R_H(\%)=30\%$ and s:1.1–1.5). The lines of sigma greater than 1.0 are drawn in this figure and the regions with sigma > 2.0 are represented by the black areas; (b) sigma distribution derived from the analysis of the contour map (Fig. 3a).

large Ne can be found in a certain region surrounding the galactic center. On the other hand, the arrival directions of general air showers show uniform distribution in the equatorial coordinates and different tendency from hadronless air showers. These hadronless air showers have been selected under very strict hadronless conditions, although a quantitative estimate of the degree of hadronless shower is difficult in this

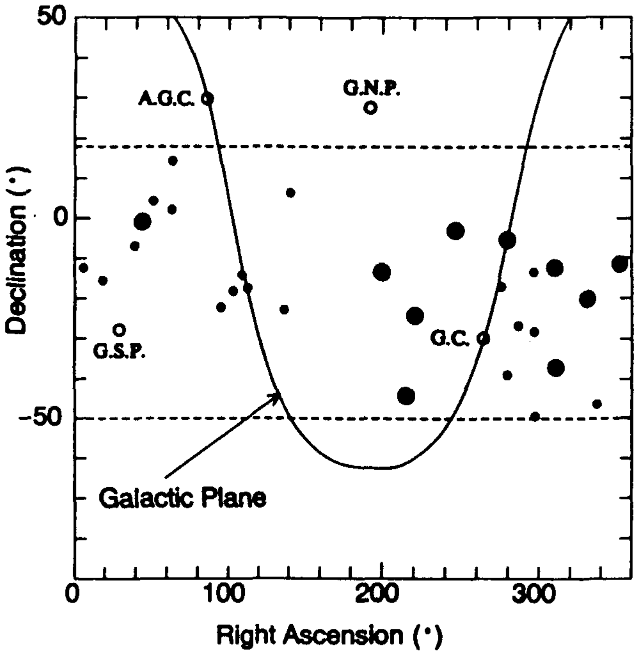

FIG. 4. The arrival directions for selected hadronless air showers with $Ne > 10^{5.0}$ and sec $\theta < 1.2$, together with a line of the galactic plane. The showers with $Ne > 1.5 \times 10^{5.0}$ are shown by large closed circles in this figure. Showers are selected with a strict regulation (see the text) on their core positions which are located above the area of the hadron detector.

case. Therefore, hadronless air showers with these special selections can be considered as candidate showers initiated by gamma rays with the best confidence. Tien Shan experiment[7] pointed out that the arrival directions of muonless showers were concentrated at a galactic latitude $> 50°$ from the observation covering δ: $15° \sim 70°$, which could be summarized with our results in a different δ region. No definite answers can be given for the origin of these air showers in conjunction with Tien Shan results, but it is possible to speculate that gamma rays may be produced $(p + p \rightarrow \pi^0 + X)$ in the inter gas which would densely concentrate near our solar system with a large structure, because no significant anisotropy of cosmic rays with energy of $10^{15} \sim 10^{16}$ eV has been observed. Otherwise, very different gamma-ray production rate in the galaxy, which depends on the cosmic-ray energy and density of inter gas and/or quite different origin of gamma-rays (galactic/extragalactic) are expected from both results. In conclusion, it is important to observe different declination regions at different latitudes in order to confirm the present results.

We wish to thank the Bolivian staff of the Laboratorio de Fisica Cosmica de Chacaltaya for construction and operation of the air shower equipment. The air shower data were calculated using the facilities of the computer center of the Institute

for Nuclear Study, University of Tokyo. A further physical analysis was carried out at the computer center of Saitama University.

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Submitted in English by the authors