Upper Limit on the Photon Fraction in Highest-Energy Cosmic Rays from AGASA Data

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A new method to derive an upper limit on photon primaries from small data sets of air showers is developed which accounts for shower properties varying with the primary energy and arrival direction. Applying this method to the highest-energy showers recorded by the AGASA experiment, an upper limit on the photon fraction of 51% (67%) at a confidence level of 90% (95%) for primary energies above 1.25×10^{20} eV is set. This new limit on the photon fraction above the Greisen-Zatsepin-Kuzmin cutoff energy constrains the Z-burst model of the origin of highest-energy cosmic rays.

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Since their first discovery about 40 years ago [1], the existence of particles with energies around and above 100 EeV $= 10^{20}$ eV was confirmed by several air shower experiments using different measurement techniques [2–7]. The quest for the nature and origin of these extremely high-energy (EHE) cosmic rays continues to drive considerable experimental and theoretical effort [8]. As first pointed out by Greisen, Zatsepin, and Kuzmin [9], the travel distance of EHE particles is limited due to energy losses on background radiation fields. For instance, the energy loss length of 200 EeV protons is $\simeq 30$ Mpc (e.g., [8,10]). A cosmological origin of the observed EHE particles thus seems disfavored. However, no astrophysical object in our cosmological vicinity could be identified yet as the source of these events. Moreover, explaining efficient particle acceleration to such enormous energies poses a theoretical challenge. The acceleration problem is circumvented if EHE particles are generated in decays or annihilation of topological defects (TD) or superheavy dark matter (SHDM) [11–14]. These objects are expected in certain inflation scenarios and have also been proposed as dark matter candidates.

A common feature of such nonacceleration models is the large fraction of EHE photons in the injected particle spectrum. Because of interactions of these photons with background fields, the diffuse photon flux at GeV energies allows one to derive an upper limit on the electromagnetic energy injected as EHE particles at distances beyond a few Mpc [15,16]. This constrains nonacceleration models which predict particle injection at large distances [12,17]. In turn, models with injection sites closer to the observer imply a significant fraction of primary photons in the observed EHE events. As an example, in the SHDM model metastable particles of mass $M_x \simeq 10^{14}$ GeV are clumped in the galactic halo and produce EHE photons, nucleons, and neutrinos by decay [12]. Thus, stringent limits on the EHE photon fraction provide constraints on nonacceleration models complementary to those from the GeV photon background.

Based on an analysis of muons in air showers observed by the Akeno Giant Air Shower Array (AGASA), upper limits on the photon fraction were estimated to be 28% above 10 EeV and 67% above 32 EeV (95% C.L.) [5]. Comparing rates of near-vertical showers to inclined ones, upper limits of 48% above 10 EeV and 50% above 40 EeV (95% C.L.) were deduced from Haverah Park data [4]. Nonacceleration models of cosmic-ray origin are not severely constrained by these bounds [18], however. Photons are predicted to reach a considerable fraction only at highest energies, while with decreasing energies below 100 EeV the "conventional" hadronic cosmic-ray component soon outnumbers photon primaries due to the steep flux spectrum. For instance, based on the SHDM model the photon fraction above 40 EeV is estimated as $\simeq 25\%$ only, increasing to $\simeq 50\%$ at 70 EeV [12].

In this work, we focus on events above 100 EeV. These particles are most directly linked to the production scenario in nonacceleration models, and the predicted photon dominance can be checked with the data. The largest data set on EHE events available to date was obtained by the AGASA experiment. From 11 AGASA showers reconstructed with energies above 100 EeV, the muon content in the shower is measured in six [5,19]. For each event, adopting its reconstructed primary parameters, we compare the observed muon signal to results from shower simulations for primary photons. In contrast to the analysis method in Ref. [5], where the data distribution above energies of 10 EeV and 32 EeV was compared to an overall simulated distribution, we thus use the information about the individual event characteristics. We develop a new statistical method that allows us to combine the information from all events and to set a limit on the primary photon contribution.

AGASA [5,20] consisted of 111 array detectors spread over $\simeq 100$ km^2 area and 27 muon detectors with an energy threshold of 0.5 GeV for vertically incident muons. The primary energy was determined with a statistical accuracy of $\simeq 25\%$ for hadron primaries [19]. Assuming photon primaries, the energies reconstructed this way were found to be underestimated by $\simeq 20\%$ for the most-energetic events [5]. Six events were reconstructed with >100 EeV which had more than one muon detector within 800–1600 m distance from the shower core [5]. The muon density ρ_j at 1000 m core distance was obtained for each event $j = 1 \ldots 6$ by fitting an empirical lateral distribution function [21] to the data. The uncertainty estimated for the resulting ρ_j is 40% [5]. The reconstructed shower parameters of the highest-energy events with muon data are given in Table I.

It is well known that photon-initiated showers generally contain significantly fewer muons than hadron-induced events. For each AGASA event, 100 primary photon showers were generated. The reconstructed primary direction [19] was chosen as simulation input, and the primary energy varied from shower to shower according to the reconstruction uncertainty. The energy was also globally increased by 20% to account for the energy underestimation in case of photons. Electromagnetic cascading of photons in the geomagnetic field was simulated for the AGASA site with the new PRESHOWER code [22]. For the AGASA events, in most cases preshower formation occurred (see Table I). The resulting atmospheric shower was simulated with CORSIKA 6.18 [23] as a superposition of subshowers initiated by the preshower particles or, if no preshower occurred, with the original primary photon. Electromagnetic interactions were treated by the EGS4 code [24], which was upgraded [23] to take photonuclear reactions as well as the Landau-Pomeranchuk-Migdal effect [25] into account. For the photonuclear cross section, we chose the extrapolation recommended by the Particle Data Group ($\sigma^{\rm PDG}$) [26,27] shown in Fig. 1. The influence of assuming different extrapolations is discussed below. Hadron interactions were simulated with QGSJET 01 [28] and for energies <80 GeV with GHEISHA [29].

The distribution $\rho_j^{\rm s}$ of simulated muon densities obtained from CORSIKA for each AGASA event is given in Fig. 2 together with the data. The average values $\langle\rho_j^{\rm s}\rangle$ and standard deviations $\Delta\rho_j^{\rm s}$ are listed in Table I. The average muon densities for primary photons are a factor 2–7 below the data. To quantify the level of agreement between data and primary photon expectation, a χ_j^2 value is calculated for each event j as

TABLE I. Reconstructed shower parameters of the AGASA events [5] (upper part of the table) and simulation results (lower part). The energies are increased by 20% to account for the case of photon primaries [5]. The azimuth angle is given clockwise from north for the incoming direction.

Primary energy [EeV]	295	240	173	161	126	125
Zenith angle [°]	37	23	14	35	33	37
Azimuth angle [°]	260	236	211	55	108	279
ρ_j [m^{-2}]	8.9	10.7	8.7	5.9	12.6	9.3
Preshower occurrence [%]	100	100	96	100	93	100
$\langle\rho_j^{\rm s}\rangle$[m^{-2}]	4.2	3.1	2.1	2.3	1.7	1.8
$\Delta\rho_j^{\rm s}$[m^{-2}]	1.1	1.0	0.9	0.6	0.5	0.5
χ_j^2	1.6	3.0	3.4	2.2	4.6	4.0
p_j[%]	20.8	8.3	6.4	13.9	3.1	4.6

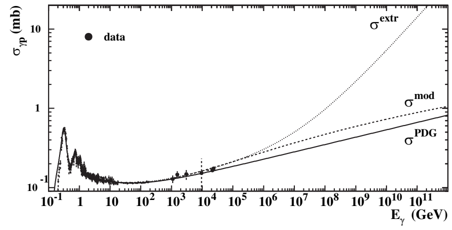

FIG. 1. Data [26] and extrapolations of the photonuclear cross section $\sigma_{\gamma p}$. The PDG extrapolation ($\sigma^{\rm PDG}$) [26,27] is chosen for this analysis. Also shown are two parametrizations with larger cross sections at highest energies, denoted $\sigma^{\rm mod}$ [37] and $\sigma^{\rm extr}$ [38] (see text). The cross section on air is taken as $\sigma_{\gamma\text{-air}} = 11.44\ \sigma_{\gamma p}$ [23,39].

$$\chi_j^2 = \frac{(\rho_j - \langle\rho_j^{\rm s}\rangle)^2}{(\Delta\rho_j)^2 + (\Delta\rho_j^{\rm s})^2} \tag{1}$$

with the measurement uncertainty $\Delta\rho_j = 0.4\rho_j$ [5]. To account for possible deviations of the simulated muon densities from a Gaussian distribution, the probability $p_j(\chi^2 \geq \chi_j^2)$ of a photon-initiated shower to yield a value $\chi^2 \geq \chi_j^2$ is determined by a Monte Carlo technique: A simulated muon density is taken at random from the distribution $\rho_j^{\rm s}$, a random shift is performed according to the experimental resolution $\Delta\rho_j$, and a χ^2 value is calculated with Eq. (1), replacing ρ_j by the artificial muon density value. Repeating this many times gives $p_j(\chi^2 \geq \chi_j^2)$. The values χ_j^2 and p_j are listed for the six events in Table I. The probabilities p_j range from 3% to 21%.

The combined probability $p(\chi^2 \geq \sum_{j=1}^{6} \chi_j^2)$ of six photon-initiated events to yield a χ^2 value larger or equal to the measured one is $p = 0.5\%$. Thus, it is unlikely that all cosmic rays at these energies are photons (rejection with 99.5% confidence), and it is possible to derive an upper limit on the primary photon fraction F_γ.

It should be noted that, due to the small event statistics, the upper limit cannot be smaller than a certain value. Assuming a primary photon fraction F_γ, a set of $n_{\rm m}$

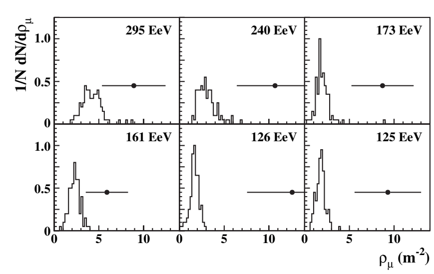

FIG. 2. Observed muon densities (points with error bars) compared to the muon densities expected for primary photons (histograms) for the six events. Assigned to each event is the primary energy (see Table I). The measured muon densities are larger than predicted for primary photons.

primaries picked at random *ab initio* does not contain any photon with probability $(1 - F_\gamma)^{n_m}$. For $n_m = 6$, this probability is $\simeq 5\%$ for $F_\gamma = 40\%$. Thus, in the present case only hypothetical photon fractions $F_\gamma \geq 40\%$ could, in principle, be tested at a confidence level of 95%.

For deriving an upper limit $F_\gamma^{ul} < 100\%$, scenarios have to be tested in which $n_\gamma = 0 \ldots n_m$ showers out of n_m events might be initiated by photons. For a hypothetical photon fraction F_γ, the probability q that a set of n_m events contains n_γ photons is $q(F_\gamma, n_\gamma, n_m) = F_\gamma^{n_\gamma}(1 - F_\gamma)^{n_m - n_\gamma}\binom{n_m}{n_\gamma}$. This probability is multiplied by the probabilities $p_\gamma(n_\gamma)p_{\bar{\gamma}}(n_m - n_\gamma)$, with $p_\gamma(n_\gamma)$ being the probability that the n_γ most photonlike looking events are generated by photons and $p_{\bar{\gamma}}(n_m - n_\gamma)$ being the probability that the remaining $n_m - n_\gamma$ events are due to nonphoton primaries. $p_\gamma(n_\gamma)$ is determined by the Monte Carlo technique as the probability to obtain values $\chi^2 \geq \sum_{i=1}^{n_\gamma} \chi_{k_i}^2$, with $p_\gamma(0) = 1$ and with $\chi_{k_i}^2 = \chi_j^2$ from Table I, where the index k_1 refers to the event with smallest value χ_j^2, and $\chi_{k_i}^2 \leq \chi_{k_{i+1}}^2$. To derive an upper limit on photons, the probabilities $p_{\bar{\gamma}}(n_m - n_\gamma)$ are set to unity. Summing over all possibilities $n_\gamma = 0 \ldots n_m$ then gives the probability $P(F_\gamma)$ to obtain χ^2 values at least as large as found in the data set,

$$P(F_\gamma) = \sum_{n_\gamma=0}^{n_m} q(F_\gamma, n_\gamma, n_m)p_\gamma(n_\gamma)p_{\bar{\gamma}}(n_m - n_\gamma). \quad (2)$$

This probability depends on the assumed photon fraction F_γ. For the considered data set, one obtains $P(F_\gamma = 51\%) = 10\%$ and $P(F_\gamma = 67\%) = 5\%$. Therefore, the upper limit on the primary photon fraction is $F_\gamma^{ul} = 51\%$ (67%) at 90% (95%) confidence level.

The derived bound is the first experimental limit on the photon contribution above the Greisen-Zatsepin-Kuzmin cutoff energy. The limit refers to the photon fraction integrated above the primary photon energy that corresponds to the lowest-energy event in the data sample, which in the present analysis is 125 EeV. In Fig. 3, upper limits derived previously at lower energy and the current bound are compared to some predictions based on nonacceleration models. Models predicting photon dominance at highest energies are disfavored by the new upper limit.

The statistical stability of the upper limit can be tested by, e.g., omitting one event and calculating an upper limit with the remaining five. Iterating through all six possibilities of rejecting an event, the upper limits are between 61%–78% (95% C.L.). Alternatively, the 320 EeV Fly's Eye event can be added to the event list with the photon probability of 13% [30]. The upper limit then is 66% (95% C.L.). The result is quite stable, as the individual photon probabilities do not differ much from each other.

The upper limit derived in the present analysis is conservative with respect to different sources of systematic uncertainties, since p_j might be overestimated. As an example, in the 295 EeV event data, muon detectors saturated and the obtained ρ_j might rather be regarded as a lower limit [5,31]. Concerning the simulations, ρ_j^s is robust when changing the low-energy hadronic interaction model [32]. The applied high-energy model QGSJET 01 produces $\simeq$ 20%–30% more muons [33] compared to SIBYLL 2.1 [34] and also compared to a preliminary version of QGSJET II [35]. Smaller values of ρ_j^s or, in case of the 295 EeV event, a larger value of ρ_j would decrease p_j and reduce the photon upper limit.

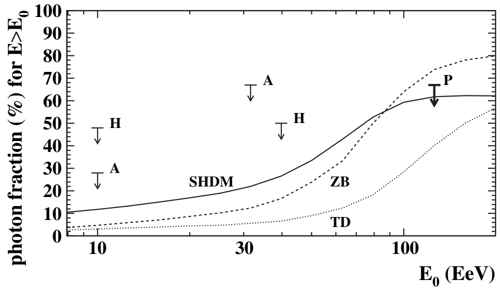

FIG. 3. Upper limits (95% C.L.) on cosmic-ray photon fraction derived in the present analysis (P) and previously from AGASA (A) [5] and Haverah Park (H) [4] compared to some predictions from SHDM [12], Z-burst (ZB), and TD [13] models.

The derived upper limit is robust against reasonable variations of the primary photon energy adopted. In general, a larger primary energy would result in larger values of ρ_j^s and p_j. We already accounted for a possible 20% underestimation in case of primary photons. It seems unlikely that an additional, systematic underestimation of reconstructed primary photon energies of more than 20%–30% exists, also because of the stronger preshower effect at increased energy that makes the profiles of primary photon showers more similar to hadron-initiated events. In turn, a rescaling of AGASA energies to smaller values would make the muon densities predicted for photons even more discrepant to the data.

A considerable uncertainty exists in extrapolating the photonuclear cross section. A stronger (weaker) increase of the cross section with energy than adopted in this work leads to larger (smaller) values of ρ_j^s. We repeated the calculations with different cross-section assumptions. The upper limit of 67% (95% C.L.) changes little for modest variations of the extrapolation. Adopting, for instance, the parametrization denoted σ^{mod} in Fig. 1, the upper limit becomes 75% (95% C.L.). However, as an illustration, assuming the extreme extrapolation labeled σ^{extr} (Fig. 1), the simulated ρ_j^s are increased on average by 70%–80% with respect to the calculation using σ^{PDG}. In such a scenario, one would obtain $P(\sigma^{extr}, F_\gamma = 100\%) \simeq 15\%$, and no upper limit could be set with high confidence. Also the previous limits from Haverah Park and AGASA data [4,5] would increase when assuming σ^{extr}.

In summary, we introduced a new method for deriving an upper limit on the cosmic-ray photon fraction from air shower observations. Applied to the highest-energy AGASA events, an upper limit of 67% (95% C.L.) is obtained for cosmic rays >125 EeV. This photon bound imposes constraints on nonacceleration models of cosmic-ray origin, with possible implications also on the description of the dark matter or inflation scenarios in these models. Within the next few years, a considerable increase of EHE event statistics is expected from the HiRes detector [6] and the Pierre Auger Observatory [36]. Thus, even more stringent conclusions on EHE photons are possible by performing an analysis as presented here. It will be studied elsewhere to what extent a scenario of dominant EHE photons together with a large photonuclear cross section can be tested with shower data.

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