Upper limit on the photon fraction in highest-energy cosmic rays from AGASA data

M. Risse, P. Homola, R. Engel, D. Góra, D. Heck, J. Pękala, B. Wilczyńska, and H. Wilczyński

(1) Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland
(2) Forschungszentrum Karlsruhe, Institut für Kernphysik, 76021 Karlsruhe, Germany

*Corresponding author. Electronic address: markus.riese@ik.fzk.de

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 GZK cutoff energy constrains the Z-burst model of the origin of highest-energy cosmic rays.

PACS numbers: 96.40.Pq, 96.40.-z, 13.85.-t, 13.85.Tp

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, 3, 4, 5, 6]. The quest for the nature and origin of these extremely high-energy (EHE) cosmic rays continues to drive considerable experimental and theoretical efforts [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 $\geq 30$ Mpc (e.g. [10]). A cosmological origin of the observed EHE particles thus seems disfavoured. However, no astrophysical object in our cosmological vicinity could be identified yet as 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 super-heavy dark matter (SHDM) [11, 12, 13, 14]. These objects are expected in certain inflation scenarios and have also been proposed as dark matter candidates.

A common feature of such non-acceleration models is the large fraction of EHE photons in the injected particle spectrum. Due to 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 non-acceleration models which predict particle injection at large distances [12]. 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 $M_{\chi} \simeq 10^{14}$ 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 non-acceleration 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% CL) [5]. Comparing rates of near-vertical showers to inclined ones, upper limits of 48% above 10 EeV and 50% above 40 EeV (95% CL) were deduced from Haverah Park data [4]. Non-acceleration models of cosmic-ray origin are not severely constrained by these bounds [15], 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 non-acceleration 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 eleven 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 [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 $\rho_j$ 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 $\rho_j$ is 40% \cite{10}. The reconstructed shower parameters of the highest-energy events with muon data are given in Tab. II.

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 \cite{11} was chosen as simulation input and the primary energy varied from shower to shower according to the reconstruction uncertainty. The energy was extrapolated recommended by the Particle Data Group \cite{25} into the Landau-Pomeranchuk-Migdal (LPM) effect \cite{25} into account. For the photonuclear cross-section, we chose the extrapolation recommended by the Particle Data Group (\sigma_{\text{PDG}}) \cite{26,27} shown in Fig. 1. The influence of assuming different extrapolations is discussed below. For deriving an upper limit on the primary photon fraction $F_{\gamma}$, a set of simulation runs was performed for $n_m$ primary photons out of a total of $N$ showers, and a $\chi^2$ value was calculated for six events in Tab. II. The probabilities $p_j$ range from 3% to 21%.

The combined probability $p(\chi^2 \geq \chi^2_j)$ of six photon-initiated events to yield a $\chi^2$ value larger or equal to the measured one is $p = 0.95$. 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 $F_{\gamma}$.

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 $F_{\gamma}$, a set of $n_m$ primaries picked at random \textit{ab initio} does not contain any photon with probability $(1-F_{\gamma})^{n_m}$. For $n_m=6$, this probability is $\approx 5\%$ 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 $F_{\gamma}^{\text{ul}}<100\%$, scenarios have to be tested in which $n_\gamma=0 \ldots n_m$ showers out of $n_m$...
FIG. 3: Upper limits (95% CL) on cosmic-ray photon fraction derived in the present analysis (P) and previously from AGASA (A) and Haverah Park (H) compared to some predictions from super-heavy dark matter (SHDM), Z-burst (ZB) and topological defect (TD) models.

events might be initiated by photons. For a hypotheti-
cal photon fraction $F_\gamma$, the probability $p$ that a set of $n_m$ events contains $n_\gamma$ photons is $q(F_\gamma, n_\gamma, n_m) = F_\gamma^n (1 - F_\gamma)^{n_m - n_\gamma} (n_m)$. This probability is multiplied by the probabilities $p_\gamma(n_\gamma) \cdot \rho_\gamma(n_m - n_\gamma)$, with $p_\gamma(n_\gamma)$ being the probability that the $n_\gamma$ most photon-like looking events are generated by photons, and $\rho_\gamma(n_m - n_\gamma)$ being the probability that the remaining $n_m - n_\gamma$ events are due to non-photon primaries. $p_\gamma(n_\gamma)$ is determined by the MC technique as the probability to obtain values $\chi^2 \geq \sum_{i=1}^{n_\gamma} \chi_i^2$, with $p_\gamma(0)=1$ and with $\chi_i^2 = \chi_j^2$ from Tab. I where the index $k_i$ refers to the event with smallest value $\chi_i^2$, and $\chi_i^2 \leq \chi_{k+1}^2$. To derive an upper limit on photons, the probabilities $\rho_\gamma(n_m - n_\gamma)$ are set to unity. Summing over all possibilities $n_\gamma = 0 \ldots n_m$ then gives the probability $P(F_\gamma)$ to obtain $\chi^2$ values at least as large as found in the data set,

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

This probability depends on the assumed photon fraction $F_\gamma$. 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 $F_\gamma^{extr} = 51\% (67\%)$ at 90\% (95\%) confidence level.

The derived bound is the first experimental limit on the photon contribution above the GZK 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 non-acceleration models. Models predicting photon dominance at highest energies are disfavoured 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\% CL). Alternatively, the 320 EeV Fly’s Eye event can be added to the event list with the photon probability of 13\%. The upper limit then is 66\% (95\% CL). 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 $p_\gamma$ might be overestimated. As an example, in the 295 EeV event data, muon detectors saturated and the obtained $p_\gamma$ might rather be regarded as a lower limit [2]. Concerning the simulations, $\rho_\gamma$ is robust when changing the low-energy hadronic interaction model [36]. The applied high-energy model QGSJET 01 produces $\pm 20$-30\% more muons [30] compared to SIBYLL 2.1 [37] and also compared to a preliminary version of QGSJET II [38]. Smaller values of $\rho_\gamma$ or, in case of the 295 EeV event, a larger value of $p_\gamma$, would decrease $p_\gamma$ and reduce the photon upper limit.

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 $\rho_\gamma$ and $p_\gamma$. 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 photontuclear cross-section. A stronger (weaker) increase of the cross-section with energy than adopted in this work leads to larger (smaller) values of $\rho_\gamma$. We repeated the calculations with different cross-section assumptions. The upper limit of 67\% (95\% CL) changes little for modest variations of the extrapolation. Adopting, for instance, the parametrization denoted $\sigma_{mod}$ in Fig. I the upper limit becomes 75\% (95\% CL). However, as an illustration, assuming the extreme extrapolation labeled $\sigma_{extr}$ (Fig. I), the simulated $\rho_\gamma$ are increased on average by 70-80\% with respect to the calculation using $\sigma_{PDG}$. 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 detector [4] and the Pierre Auger Observatory [51] would increase when assuming $\sigma_{extr}$.

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\% CL) is obtained for cosmic rays $>125$ EeV. This photon bound imposes constraints on non-acceleration 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 [12] and the Pierre Auger Observatory [33]. Thus, even more stringent conclusions on EHE photons are possible by performing an analysis as presented here. It will
be studied elsewhere, to what extend a scenario of dominant EHE photons together with a large photonuclear cross-section can be tested with shower data.

Acknowledgments. We are grateful to K. Eitel, M. Jeżabek, M. Kachelrieß, S.S. Ostapchenko, S. Sarkar, K. Shinozaki, and G. Sigl for helpful comments. This work was partially supported by the Polish State Committee for Scientific Research under grants No. PBZ KBN 054/P03/2001 and 2P03B 1104 and in Germany by the DAAD under grant No. PPP 323. MR is supported by the Alexander von Humboldt-Stiftung.

[1] J. Linsley, Phys. Rev. Lett. 10, 146 (1963).
[2] D.J. Bird et al., Phys. Rev. Lett. 71, 1301 (1993); D.J. Bird et al., Astrophys. J. 441, 144 (1995).
[3] N. Hayashida et al., Phys. Rev. Lett. 73, 3491 (1994); M. Takeda et al., Phys. Rev. Lett. 81, 1163 (1998).
[4] M. Ave et al., Phys. Rev. Lett. 85, 2244 (2000); M. Ave et al., Phys. Rev. D65, 063007 (2002).
[5] K. Shinozaki et al., Astrophys. J. 571, L117 (2002).
[6] R.U. Abbasi et al., Phys. Rev. Lett. 92, 151101 (2004).
[7] V.P. Egorova et al., astro-ph/0408493 (2004).
[8] V.P. Egorova et al., astro-ph/0408493 (2004).
[9] K. Greisen, Phys. Rev. Lett. 16, 748 (1966); G.T. Zatsepin, V.A. Kuzmin, JETP Lett. 4, 78 (1966).
[10] F.W. Stecker, Phys. Rev. Lett. 21, 1016 (1968).
[11] C.T. Hill, Nucl. Phys. B224, 469 (1983); M.B. Hindmarsh, T.W.B. Kibble, Rep. Prog. Phys. 58, 477 (1995); V. Berezhinsky, M. Kachelrieß, A. Vilenkin, Phys. Rev. Lett. 79, 4302 (1997); M. Birkel, S. Sarkar, Astropart. Phys. 9, 297 (1998); V.A. Kuzmin, V.A. Rubakov, Phys. At. Nucl. 61, 1028 (1998); Z. Fodor, S.D. Katz, Phys. Rev. Lett. 86, 3224 (2001); S. Sarkar, R. Toldra, Nucl. Phys. B621, 495 (2002); C. Barbot, M. Drees, Astropart. Phys. 20, 5 (2003); S. Sarkar, Acta Phys. Polon. B35, 351 (2004).
[12] R. Aloisio, V. Berezhinsky, M. Kachelrieß, Phys. Rev. D69, 094023 (2004).
[13] G. Sigl, hep-ph/0109220 (2001).
[14] P. Bhattacharjee, G. Sigl, Phys. Rep. 327, 109 (2000).
[15] V.S. Berezhinsky, A.Yu. Smirnov, Ap. Sp. Sci. 32, 461 (1975); G. Sigl, Science 291, 73 (2001).
[16] P. Sreekumar et al., Astrophys. J. 494, 523 (1998); A.W. Strong et al., astro-ph/0405441 (2004).
[17] D.V. Semikoz, G. Sigl, JCAP 0404, 003 (2004).
[18] M. Kachelrieß, C.R. Physique 5, 441 (2004).
[19] M. Takeda et al., Astropart. Phys. 19, 447 (2003); N. Hayashida et al., astro-ph/0008102 (2000); M. Takeda et al., Astrophys. J. 522, 225 (1999); http://www-akeno.icrr.u-tokyo.ac.jp/AGASA.
[20] N. Chiba et al., Nucl. Instr. Meth. A311, 338 (1992); H. Oboka et al., Nucl. Instr. Meth. A385, 268 (1997).
[21] M. Takeda et al., Nucl. Instr. Meth. A311, 338 (1992); H. Oboka et al., Nucl. Instr. Meth. A385, 268 (1997).
[22] N. Hayashida et al., J. Phys. G21, 1001 (1995).
[23] P. Homola et al., astro-ph/0311442 (2003).
[24] D. Heck et al., Report F43K 6019, and D. Heck, J. Knapp, Report F43K 6097, Forschungszentrum Karlsruhe (1998).
[25] W.R. Nelson, H. Hirayama, D.W.O. Rogers, Report SLAC 265, Stanford Linear Accelerator Center (1985).
[26] L.D. Landau, I.Ya. Pomeranchuk, Dokl. Akad. Nauk SSSR 92, 535 & 735 (1953) (in Russian); A.B. Migdal, Phys. Rev. 103, 1811 (1956).
[27] S. Eidelmann et al., Particle Data Group, Phys. Lett. B592, 1 (2004).
[28] J.R. Cudell et al., Phys. Rev. D65, 074020 (2002).
[29] L. Bezrukov, E. Bugaev, Sov. J. Nucl. Phys. 33, 635 (1981).
[30] A. Donnachie, P. Landshoff, Proc. 27th Int. Cosmic Ray Conf., Hamar, 329 (2001).
[31] H. Genzel et al., in: Landolt-Börnstein, New Series I/8, Springer, Berlin (1973).
[32] N.N. Kalmykov, S.S. Ostapchenko, A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.) 52, 17 (1997).
[33] H. Fesefeldt, Report PITHA-85/02, RWTH Aachen (1985).
[34] M. Risse et al., Astropart. Phys. 21, 479 (2004).
[35] N. Sakaki et al., Proc. 27th Int. Cosmic Ray Conf., Hamburg, 329 (2001).
[36] D. Heck, astro-ph/0410735 (2004).
[37] D. Heck, M. Risse, J. Knapp, Nucl. Phys. B (Proc. Suppl.) 122, 451 (2004).
[38] R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, Proc. 26th Int. Cosmic Ray Conf., Salt Lake City, 415 (1999).
[39] S.S. Ostapchenko, hep-ph/0501093 (2005).
[40] J. Abraham et al., Auger Collaboration, Nucl. Instrum. Meth. A523, 50 (2004); J. Blümer for the Auger Collaboration, J. Phys. G29, 867 (2003).