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Constraints on the flux of primary cosmic-ray photons at energies $E > 10^{18}$ eV from Yakutsk muon data

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Comparing the signals measured by the surface and underground scintillator detectors of the Yakutsk Extensive Air Shower Array, we place upper limits on the integral flux and the fraction of primary cosmic-ray photons with energies $E > 10^{18}$ eV, $E > 2 \times 10^{18}$ eV, and $E > 4 \times 10^{18}$ eV. The large collected statistics of the showers measured by large-area muon detectors provides a sensitivity to photon fractions $<10^{-2}$, thus achieving precision previously unreachable at ultrahigh energies.

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I. INTRODUCTION

Ultra-high-energy (UHE) cosmic-ray (CR) photons are produced by energetic protons and nuclei in their interactions both at acceleration sites and along their trajectories towards the Earth [1]. Both protons and heavier nuclei with energies $E \sim 10^{20}$ eV interact with cosmic background radiations, especially with cosmic microwave background (CMB) and infrared background (IRB) radiation. The processes involved in these interactions are however very different. Interactions of a *proton* at $E \gtrsim 7 \times 10^{19}$ eV with CMB photons lead to efficient pion production [2,3]. Further decays of neutral pions produced in these interactions lead to a secondary photon flux at energies $E \gtrsim 10^{18}$ eV (so-called Greisen–Zatsepin–Kuzmin photons) [4,5]. On the other hand, the dominant interaction channel for *heavier nuclei* is their photodisintegration on IRB photons; the secondary photon flux is much smaller in this case [6]. Therefore, the photon flux at $E \gtrsim 10^{18}$ eV may provide an independent test of the chemical composition of CRs at $E \sim (10^{19} \ldots 10^{20})$ eV which is, at present, largely uncertain [7–10].

On the other hand, the study of UHE photons is a powerful tool for constraining new-physics models. One example is provided by models with superheavy dark-matter (SHDM) particles (e.g. [11]); a substantial fraction of the SHDM decay products are photons. Another class of exotic relics to be searched for with CRs is topological defects [12,13]; UHE photons were suggested [14] as their signature. With the help of UHE photons, one may also constrain astrophysical models of the CR origin which involve new physics at the propagation stage. In particular, both the spectrum and the chemical composition of CRs are changed in models with violation of the Lorentz invariance [15]. The photon fraction at the highest energies is sensitive to parameters violating Lorentz invariance, and upper limits on the former severely constrain the latter [16]. Finally, photons with energies above $\sim 10^{18}$ eV might be responsible for CR events correlated with BL Lac type objects on the angular scale significantly smaller than the expected deflection of protons in cosmic magnetic fields and thus suggesting neutral primaries [17,18] (see Ref. [19] for a particular mechanism).

In this paper, we present the analysis of extensive air showers observed by the Yakutsk extensive-air-shower array, which yields the strongest limits on the photon flux and the photon fraction in CRs at energies $E > 10^{18}$ eV, $E > 2 \times 10^{18}$ eV, and $E > 4 \times 10^{18}$ eV. These limits enter the region interesting both for highest-energy astrophysics and tests of extragalactic backgrounds as well as for searches of new physics. To obtain better quantitative constraints it would be helpful to use the results of other experiments jointly with ours; it will be done elsewhere.

II. METHOD

The key idea of our method is the event-by-event comparison of the observed muon densities in air showers with those in simulated gamma-ray induced showers which have the same signal density as measured by the surface scintillator array and have the same arrival direction as the observed ones. The method is described in detail in Ref. [20]; it has been previously applied to Yakutsk and AGASA muon data at the highest energies [21,22]. Similar statistical methods have been used to constrain primary photon content from the data collected by the fluorescent detector of the Pierre Auger Observatory [23] (see also Ref. [24]). One of the advantages of the method is its independence both from the energy-reconstruction procedure used by the experiment and from the Monte-Carlo simulation of hadronic air showers: we use simulated gamma-ray induced showers which are mostly electromagnetic and are therefore well understood and we select the simulated showers by the observable signal density in the surface scintillator array and not by the energy (effectively estimating the energy of each event in the assumption of a photon primary).

The Yakutsk extensive-air-shower array (Yakutsk, Russia) has been observing UHECR events since 1973, with detectors in various configurations [25–27] covering an area from 10 km^2 to 20 km^2 in different operation periods. For the data set used in this work, the surface array comprised 49 (before 1990, 41) detectors, where each detector consisted of two 2 m^2 scintillation counters. It is equipped, since 1982, with five muon detectors of 20 m^2 area each with threshold energy 1 GeV for vertical muons [28]. A sketch of the Yakutsk array is presented in Fig. 1.

At present, it is the only installation in the world which is equipped with muon detectors and capable of studying CRs with energies above 10^{18} eV. The surface scintillator detector signal density at 600 m from the shower axis, $S(600)$, together with the shower geometry, is obtained from a joint fit of the lateral distribution function and the shower front arrival times [29]. For the events we use, the angular resolution is $\approx 5°$ and the mean $S(600)$ resolution is $\approx 17\%$. The energy of a primary particle is estimated in the Yakutsk experiment from $S(600)$ and the zenith angle as described in Refs. [27,30], by making use of the experimental calibration to the atmospheric Cerenkov light [31] and of the attenuation curve determined from data by means of the constant intensity cuts method suggested in Ref. [32] and used also by the Haverah Park [33], AGASA [34], and Auger [35] experiments. This reconstructed energy $E_{\rm est}$ may differ from the true primary energy E both due to natural fluctuations and due to possible systematic effects. These latter effects depend on the primary particle type; in particular, the difference between photons and hadrons is significant [36]. This difference in the energy estimation of primary gamma rays and primary hadrons (which constitute the bulk of observed UHECRs) forces one to use different ways of energy reconstruction when searching for photon primaries.

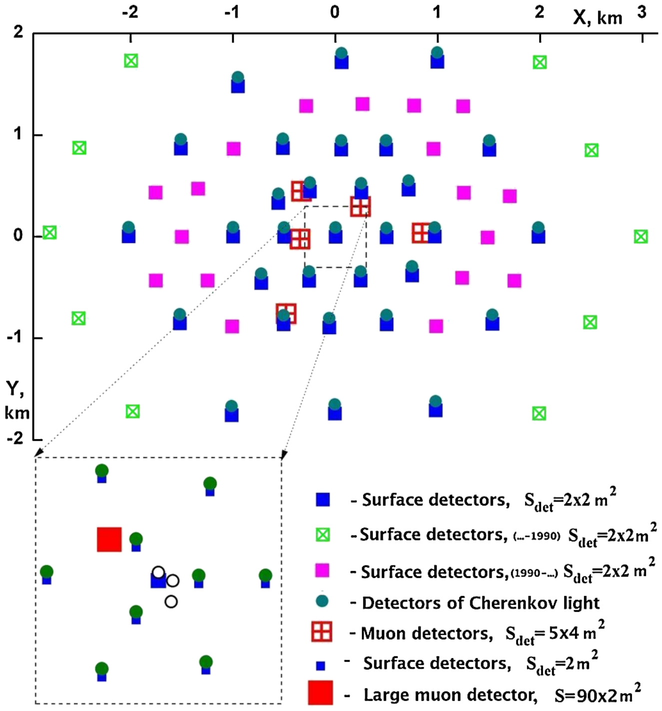

FIG. 1 (color online). A sketch of the Yakutsk array. Each surface detector consists of two 2 m^2 scintillators, while each muon detector consists of five 4 m^2 scintillators placed underground (with shielding equivalent to about 2 m thick concrete wall). The signal of the large muon detector is not used in this study as well as signal of the small central subarray outlined separately.

For the present study, we use the sample of events satisfying the following criteria: (1) the event passed the surface array trigger described in Refs. [26,27]; (2) the reconstructed core location is inside the array boundary; (3) the zenith angle $\theta \leq 45°$; (4) the reconstructed energy $E_{\rm est} \geq 10^{18}$ eV; (5) the reconstructed shower axis is within 300 m from an operating muon detector. The data set contains 1647 events observed between December 10, 1982 and June 30, 2005 and corresponds to an effective exposure of 7.4×10^8 km$^2 \cdot$ s $\cdot$ sr for $E > 10^{18}$ eV [an important reduction in the effective area is related to the cut (5)].

By making use of the empirical muon lateral distribution function [28], we calculate, for each event, the muon density at 300 m from the shower axis, $\rho_\mu(300)$, which we use as the composition estimator. We apply the event-by-event analysis following Ref. [20] and estimate, for each event, the probability that it has been initiated by a primary photon. To this end, we use a library of $\sim 2 \times 10^4$ artificial photon-induced showers with different energies (2×10^{17} eV $< E < 2 \times 10^{19}$ eV) and arrival directions, of which we select those with the same $S(600)$ and zenith angle [37] as the observed event, up to reconstruction errors (a detailed description of the method is presented in Refs. [20,21]).

To simulate the shower library, we used CORSIKA 6.611 [38] with FLUKA 2006.3 [39] as a low-energy hadronic interaction model and EPOS 1.61 [40] as a high-energy model. The difference in the expected muon density between various models is negligible for photon showers (we checked it explicitly for EPOS 1.61 and QGSJET II [41]). We used thinning (10^{-5}) with weight limitations [42] to save computational time [43].

For each simulated shower, we determine $S(600)$ and $\rho_\mu(300)$ by making use of the GEANT simulations of the detector [45]. This enables us to select simulated showers compatible with the observed ones by $S(600)$: each artificial shower gets a weight determined by the difference in $E_{\rm est}$ from the real event [46]. For each of the observed events, we calculate the distribution of simulated muon densities representing photon-induced showers compatible with the observed ones by $S(600)$ and θ in the following way. To take into account possible experimental errors in the determination of the muon density, we replace each simulated $\rho_\mu(300)$ with a Gaussian distribution representing possible statistical errors (see formulas and discussion in Ref. [20]). The latter have been estimated for each event individually by fitting muon detector readings with the lateral distribution function [20,28]. The dominant contribution to the statistical error of $\rho_\mu(300)$ comes from the uncertainty in the determination of the shower axis (for which we use the geometric reconstruction from the main scintillator array). The overall uncertainty of $\rho_\mu(300)$ varies from ~15% to ~40% for individual events. The distribution of the simulated muon densities is the weighted average of these Gaussians. For each event in the data set we derive, from this distribution, the probability $p_\gamma^{(+)}$ that it has been initiated by a primary photon of energy in the range under study ($E > E_{\rm min}$ for $E_{\rm min} = 10^{18}$ eV, 2×10^{18} eV or 4×10^{18} eV). The distribution of $p_\gamma^{(+)}$ for the observed events is presented in Fig. 2. Then Fig. 3 illustrates that for most events, the measured muon densities are too high as compared to those obtained from simulations of photon-induced showers. A simple statistical procedure [20] allows one to determine upper limits on the photon content from the ensemble of $p_\gamma^{(+)}$.

Below, we present limits on the fraction of gamma rays and on the absolute gamma-ray flux. For the fraction limits, we use explicit formulae of Ref. [20]. The fraction limits depend [22] on the energy scale assumed *for nonphoton primaries* which has a systematic uncertainty of 30% [25]. The flux limits do not depend on the choice of hadronic interaction model used in simulations, nor on the energy reconstruction used in the experiment; the only assumption is that electromagnetic showers are simulated correctly. To obtain the limit on the flux of primary photons, we slightly modified the technical part of the procedure of Ref. [20]. Let F_γ be the integral flux of primary photons over a given energy range. Then we expect to detect

$$\bar{n}(F_\gamma) = F_\gamma A(1 - \lambda)$$

photon events on average, where A is the exposure of the experiment for a given data set and λ is the fraction of "lost" photons [48] (values of λ are given in Table I). Let $\mathcal{P}(n)$ be the probability to have n photons in a data set (calculated from data following Ref. [20]). To constrain the flux F_γ at the confidence level ξ one requires

$$\sum_n \mathcal{P}(n) W(n, \bar{n}(F_\gamma)) < 1 - \xi,$$

where $W(n, \bar{n})$ is the Poisson probability to observe n particles for the average $\bar{n}$.

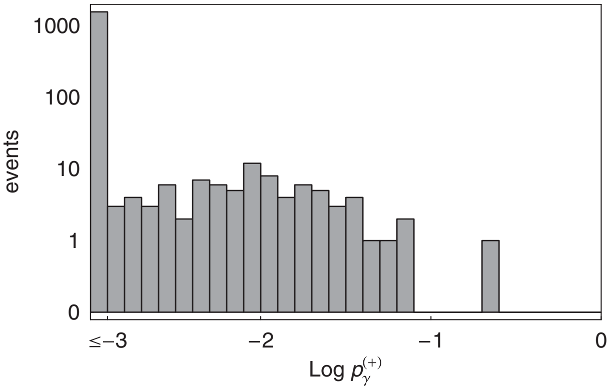

FIG. 2. Distribution of probabilities $p_\gamma^{(+)}$ for the sample of real events with the lower energy cut on energy $E_{\rm min} = 10^{18}$ eV.

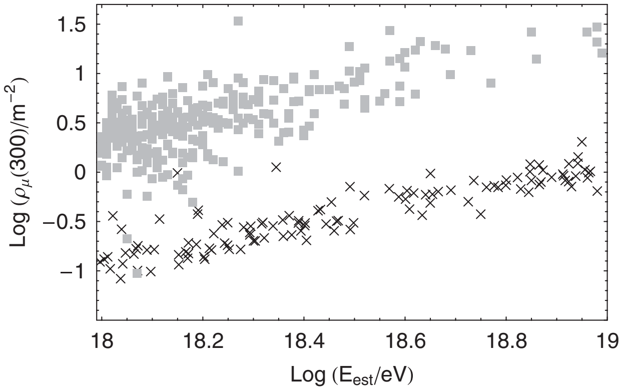

FIG. 3. Muon densities $\rho_\mu(300)$ of air showers with $30° < \theta < 35°$ versus primary energies $E_{\rm est}$ reconstructed by the standard Yakutsk procedure for simulated photon-induced events (crosses) and for real data (boxes).

TABLE I. Upper limits (95% C.L.) on the number n_γ of photons with $E > E_{\rm min}$ in the sample, on the integral flux F_γ of photons with $E > E_{\rm min}$ and on the fraction ϵ_γ of photons in the total integral flux of cosmic particles with $E > E_{\rm min}$. The flux limits do not depend on the energy reconstruction procedure; the fraction limits are given for the assumption of correct energy reconstruction for nonphoton primaries and for the supposed overall shifts of ±30% *for nonphoton primaries*. Also given are the number N of events with $E_{\rm est} > E_{\rm min}$ in the data set, the fraction of lost photons λ, the maximal $p_\gamma^{(+)}$ for a given $E_{\rm min}$ and the limits on F_γ obtained by the statistical method of Ref. [49] with our data.

$E_{\rm min}$, eV	10^{18}	2×10^{18}	4×10^{18}
n_γ	5.1	3.1	3.0
F_γ, km^{-2} sr^{-1} yr^{-1}	0.22	0.13	0.13
$E^2 F_\gamma$, 10^{35} eV^2 km^{-2} sr^{-1} yr^{-1}	2.2	5.2	20.8
ϵ_γ	0.004	0.008	0.041
ϵ_γ ($E_{\rm est}$ + 30%)	0.003	0.005	0.022
ϵ_γ ($E_{\rm est}$ − 30%)	0.006	0.018	0.108
$N(E_{\rm est} > E_{\rm min})$	1647	341	63
λ	0.02	<0.01	<0.01
max($p_\gamma^{(+)}$)	0.25	0.026	<0.001
F_γ, km^{-2} sr^{-1} yr^{-1}, method [49]	0.25	0.25	0.25

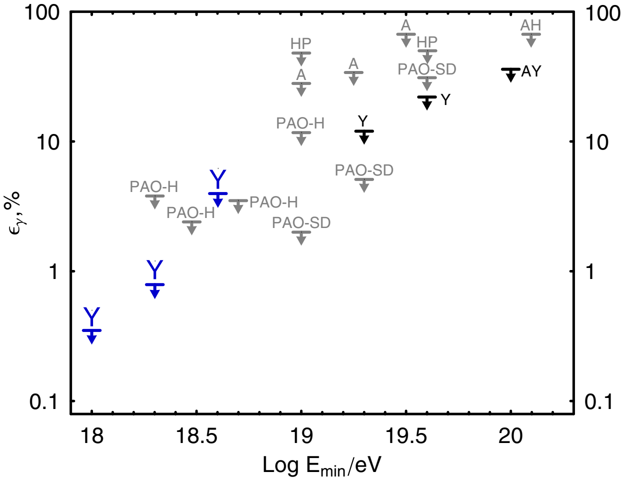

FIG. 4 (color online). Limits (95% CL) on the fraction of primary gamma rays in the integral flux of cosmic particles with $E_0 > E_{\min}$ from: this work (large Y); hybrid events of the Pierre Auger Observatory (PAO-H) [49]; the surface detector of the Pierre Auger Observatory (PAO-SD) [52]; Yakutsk (small Y) [22]; reanalysis of the AGASA (AH) [24] and AGASA and Yakutsk (AY) [21] data; AGASA (A) [53] and Haverah Park (HP) [54].

III. RESULTS

The upper limits on the observed flux and fraction of primary gamma rays are summarized in Table I. We compare the limits with those from previous works in Fig. 4 (for the gamma-ray fraction) and Fig. 5 (for the gamma-ray flux).

The energy range under study was partially explored by Auger Collaboration, which placed a limit on the photon fraction at $E > 2 \times 10^{18}$ eV [49]. We see that the result from Yakutsk is stronger than Auger limits below 3×10^{18} eV, though it is based on a smaller data set. The principal reason for this fact is related to the observable we use: the muon energy density distinguishes primary photons from hadrons better than the depth of shower maximum $X_{\max}$.

To illustrate this we applied the statistical method of Ref. [49] to our data. The Auger sample after selection and quality cuts contained about 1050 events out of which 8 events were “photon candidates” [49]. The latter were defined as events with $X_{\max}$ exceeding those of photon initiated showers in 50% cases. In Yakutsk we have 401 events of energy $E > 2 \times 10^{18}$ eV [50] with no photon candidates, that is $p_\gamma^{(+)} > 0.5$ in our language (maximal $p_\gamma^{(+)} = 0.026$). These numbers for various $E_{\min}$ together with limits on the gamma-ray flux calculated by the statistical method of Ref. [49] with our data are also presented in Table I. Our method gives slightly more restrictive limits because the maximal $p_\gamma^{(+)}$ is much lower than the Auger threshold of 50%.

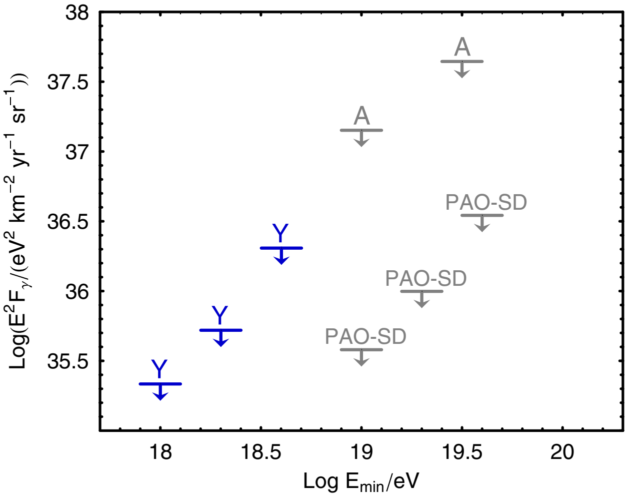

FIG. 5 (color online). Limits (95% CL) on the integral flux of primary gamma rays with $E_0 > E_{\min}$ from: this work (Y); the surface detector of the Pierre Auger Observatory (PAO-SD) [52] and AGASA (A; assume mixed proton-gamma composition) [53].

The sensitivity of plastic scintillators to electromagnetic showers, the strong discriminating power of large-area muon detectors, a 25-year exposure and a sophisticated analysis led up to the most stringent limits on the primary photon flux at energies above 10^{18} eV and 2×10^{18} eV. These limits start to fill the gap between limits on the diffuse gamma-ray flux at $\lesssim 10^{16}$ eV and $\gtrsim 10^{19}$ eV and may challenge previously allowed new-physics models. The *flux* limits do not depend on the energy reconstruction used by the experiment (a reconstruction in assumption of primary photons is used), nor on the simulations of hadronic showers. The *fraction* limits also use the energy estimation in assumption of primary photons and also do not rely on simulation of hadronic showers; however they depend on the assumed energy estimation of nonphoton primary particles [51]. This dependence is weak in the high-statistics regime, cf. Table I.

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