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Constraining the fraction of primary gamma rays at ultra-high energies from the muon data of the Yakutsk extensive-air-shower array

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By making use of the data on the total signal and on the muon component of the air showers detected by the Yakutsk array, we analyze, in the frameworks of the recently suggested event-by-event approach, how large the fraction of primary gamma-rays at ultra-high energies can be. We derive upper limits on the photon fraction in the integral flux of primary cosmic rays. At the 95% confidence level (CL), these limits are 22% for primary energies $E_0 > 4 \cdot 10^{19}$ eV and 12% for $E_0 > 2 \cdot 10^{19}$ eV. Despite the presence of muonless events, the data are consistent with complete absence of photons at least at 95% CL. The sensitivity of the results to systematic uncertainties, in particular to those of the energy determination for non-photon primaries, is discussed.

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1. Introduction. With the increase of statistics of ultra-high-energy (UHE) cosmic-ray (CR) events the study of the chemical composition at the very end of the spectrum (beyond 10^{19} eV) is becoming quite realistic. This issue is of primary interest today, in view of a systematic discrepancy between energy spectra measured by different detectors [1 – 4] and of indications towards a fraction of neutral particles among the UHECR primaries [5]. The chemical composition is also a starting point in studies of: *(i)* extragalactic magnetic fields and radiation backgrounds; *(ii)* accelaration mechanisms operating in astrophysical sources; *(iii)* possible top-down scenarios emerging in various extensions of the Standard Model of particle physics. In particular, the photon fraction in the CR flux is of crucial importance; the aim of this work is to derive stringent limits on this fraction in the integral CR flux above the energy $2 \cdot 10^{19}$ eV.

We make use of a recently suggested approach [6, 7] and perform case-by-case analysis of 50 events detected by the Yakutsk extensive-air-shower array (Yakutsk array in what follows) [1] with *reconstructed* energies above $2 \cdot 10^{19}$ eV chosen according to quality cuts described in Sec. 2. To place the limit on the photon fraction, we compare the reported information on signals measured by scintillation and muon detectors with that expected from air-shower simulations. We focus on the surface detector signal density at 600 meters $S(600)$ and the muon density at 1000 meters, $\rho_\mu(1000)$, which are used in experiments as primary energy and primary composition estimators, respectively. Among the fifty showers in the sample, two are muonless (that is, muon detectors were operating in the shower impact area but did nor detect any signal). These events are compatible with being initiated by primary gamma rays of energies $2 \cdot 10^{19}$ eV$< E_0 < 4 \cdot 10^{19}$ eV, even though the reconstructed energy exceeds $4 \cdot 10^{19}$ eV for one of them. One muon-poor shower is consistent with a photon primary of energy above $4 \cdot 10^{19}$ eV with probability about 10%. For the rest of the showers, the hypothesis of a photon primary is rejected at the 95% CL for each event. We derive upper limits on the fraction ϵ_γ of photons in the integral flux of primary cosmic rays with *actual* energies $E_0 > 2 \cdot 10^{19}$ eV and $E_0 > 4 \cdot 10^{19}$ eV (the difference between actual (E_0) and reconstructed ($E_{\rm est}$) energies is discussed in Sec. 2).

The rest of the paper is organized as follows. In Sec. 2 we discuss the experimental data set used in our study. In Sec. 3 we briefly review the approach we use and present our main results. We discuss how robust these results are with respect to changes in assumptions and in the analysis procedure and discuss the uncertainties associated with possible systematics in energy determination of observed UHECR events in Sec. 4. Sec. 5 contains our conclusions.

2. Experimental data. Yakutsk array is observing UHECR events since 1973, with detectors in various configurations. Since 1979, muon detectors with areas up to 36 m^2 (currently, five detectors of 20 m^2 each with threshold energy 1 GeV for vertical muons) supplement ground-based scintillator stations. At present, it is the only installation equipped with muon detectors capable of studying ultra-high-energy cosmic rays.

The energy of a primary particle is estimated from $S(600)$ and zenith angle with the help of the procedure described in Ref. [8], calibrated experimentally by making use of the atmospheric Cherenkov light. This reconstructed energy $E_{\rm est}$ differs from the true primary energy E_0 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. Moreover, for photons, the effects of geomagnetic field [9] result in directional dependence of the energy reconstruction. Thus, the event energy reported by the experiment should be treated with care when we allow the primary to be a photon. Because of possible energy underestimation for high-energy photon-induced showers, we use events with $E_{\rm est} \geq 2 \cdot 10^{19}$ eV even when deriving the limit for $E_0 > 4 \cdot 10^{19}$ eV; they contribute to the final limit with different weights [7].

For our study, we selected a subset of events with $E_{\rm est} \geq 2 \cdot 10^{19}$ eV satisfying the following cuts aimed at the most precise determination of both $S(600)$ and $\rho_\mu(1000)$:

(i) shower core inside the array;

(ii) zenith angle $\theta \leq 60°$;

(iii) three or more muon detectors between 400 m and 2000 m from the shower axis, operational at the moment of the shower arrival.

Our sample consists of 50 air showers; the cuts select approximately one third of the events used for the determination of the spectrum.

3. Simulations and results. The approach we use was described and discussed in detail in Refs. [6, 7] and has already been applied to a similar study of the photon fraction at energies above 10^{20} eV [6]. Here, we summarise the main steps of this approach.

For each of the events in our sample, we generated a library of simulated showers induced by primary photons. Thrown energies E_0 of the simulated showers were randomly selected within a relevant energy interval in order to take into account possible deviations of $E_{\rm est}$ from E_0, see below. The arrival directions of the simulated showers were the same as those of the corresponding real events. The simulations were performed with CORSIKA v6.5011 [10], choosing QGSJET II-03 [11] as high-energy and FLUKA 2005.6 [12] as low-energy hadronic interaction model. Electromagnetic showering was implemented with EGS4 [13] incorporated into CORSIKA. Possible interactions of the primary photons with the geomagnetic field were simulated with the PRESHOWER option of CORSIKA [14]. As suggested in Ref. [15], all simulations were performed with thinning level 10^{-5}, maximal weight 10^6 for electrons and photons, and 10^4 for hadrons.

For each simulated shower, we determined $S(600)$ and $\rho_\mu(1000)$ by making use of the detector response functions from Ref. [16]. For a given arrival direction, there is one-to-one correspondence between $S(600)$ and the estimated energy as determined by the standard analysis procedure for the Yakutsk experiment [8]. This enables us to select simulated showers compatible with the observed ones by the signal density, which follows the Gaussian distribution in log(energy); the standard deviation of $E_{\rm est}$ has been determined event-by-event and is typically 17% [17]. Namely, to each simulated shower, we assigned a weight w_1 proportional to this Gaussian probability distribution in $\log E_{\rm est}$ centered at the observed energy. Additional weight w_2 was assigned to each simulated shower to reproduce the thrown energy spectrum $\propto E_0^{-2}$ (see Sec. 4.3 for the discussion of the variation of the spectral index). For each of the observed events from our dataset, we calculated the distribution of muon densities $\rho_\mu(1000)$ representing photon-induced showers compatible with the observed ones by $S(600)$ and arrival directions. To this end, we calculated $\rho_\mu(1000)$ for each simulated shower by making use of the same muon lateral distribution function as used in the analysis of real data [18]. To take into account possible experimental errors in the determination of the muon density, we replaced each simulated $\rho_\mu(1000)$ by a distribution representing possible statistical errors (Gaussian with 25% standard deviation [6]). The distribution of the simulated muon densities is the sum of these Gaussians weighted by $w_1 w_2$.

For each event we calculate, by making use of the obtained distributions, two numbers: the probability that it could be initiated by a photon with true energy in the range of interest (that is, above $E_0 = 4 \cdot 10^{19}$ eV or above $E_0 = 2 \cdot 10^{19}$ eV) and the probability that it could be initiated by any other primary (whose energy is assumed to be determined correctly by the experiment; see Sec. 4.1 for relaxing this assumption) with energy above this E_0. For most of the events, the measured muon densities are too high as compared to those obtained from simulations of photon induced showers.

Given these probabilities for each event, we construct the likelihood function (see Ref. [7] for details) to estimate, at a given confidence level, the fraction ϵ_γ of primary photons among UHECR with energies in a given range. In this way we obtain at 95% CL

$$\epsilon_\gamma < 22\% \qquad \text{for} \quad E_0 > 4 \cdot 10^{19} \text{ eV}, \tag{1}$$

$$\epsilon_\gamma < 12\% \qquad \text{for} \quad E_0 > 2 \cdot 10^{19} \text{ eV}. \tag{2}$$

These limits include corrections for the "lost photons" (those with true energies $E_0 > 4 \cdot 10^{19}$ eV for the limit (1) and $E_0 > 2 \cdot 10^{19}$ eV for the limit (2) but reconstructed energies $E_{\rm rec} < 2 \cdot 10^{19}$ eV, see Ref. [7] for more details).

In Fig.1, we present our limits (denoted by Y) together with previously published limits[1)] on ϵ_γ. Also,

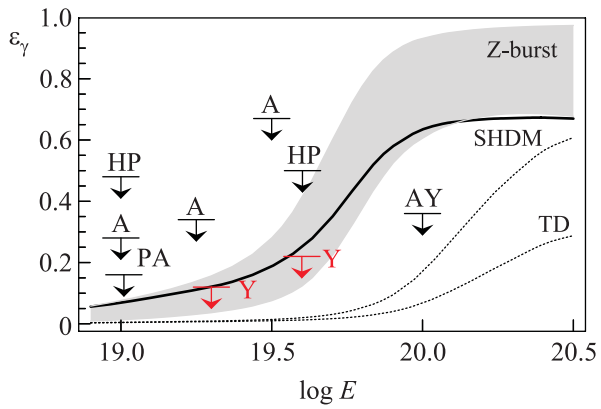

Fig.1. Limits (95% CL) on the fraction ϵ_γ of photons in the integral CR flux versus energy. The results of the present work (Y) are shown together with the limits previously given in Refs. [19] (HP), [20] (A), [6] (AY) and [21] (PA). Also shown are predictions for the superheavy dark matter model (thick line), the topological-defect models (necklaces, between dotted lines) [22] and the Z-burst model (shaded area) [23]. Theoretical curves are normalized to the AGASA spectrum [2]. Energy is measured in eV

typical theoretical predictions are shown for the superheavy dark matter, topological-defect and Z-burst models. Our limits on ϵ_γ are currently the strongest ones for the energy range under discussion. They disfavor the superheavy dark matter explanation of the highest energy events.

4. Robustness of the results. The systematic uncertainties of our results are related to the air-shower simulations and to the data interpretation. They were discussed in detail in Ref. [6] for a different data set, with the conclusion that the approach we use to constrain ϵ_γ results in quite robust limits.

4.1. *Systematic uncertainty in the $S(600)$ and energy determination.* The systematic uncertainty in the absolute energy determination by the Yakutsk array is about 30% [1]. It originates from two quite different sources: (a) the measurement of $S(600)$ and (b) the relation between $S(600)$ and primary energy. The probabilities that a particular event may allow for a gamma-ray interpretation are not at all sensitive to the $S(600)$-to-energy conversion because we select simulated events by $S(600)$ and not by energy. These probabilities may only be affected by *relative* systematics between the determinations of $\rho_\mu(1000)$ and of $S(600)$. On the other hand, we assumed that the experimental energy determination is correct for non-photon primaries; the values of probabilities that a particular event could be initiated by a non-photon primary with energy above threshold and hence the effective number of events contributing to the limit on ϵ_γ would change if the energies are systematically shifted. The effect of such a shift would be to change the energy range for which the limit is applicable and to change, by a few per cent, the limit itself. This is illustrated in Fig.2, which has been obtained

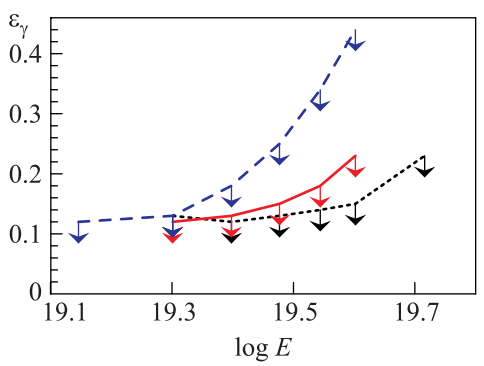

Fig.2. Sensitivity of the limit on ϵ_γ to the systematic uncertainty in the energy determination for non-photon primaries. The solid curve represents the limits assuming the energy scale quoted by Yakutsk experiment and normalized to the Cherenkov light (the same as points Y in Fig.1). The dashed and dotted curves correspond to the shifts of -30% and $+30\%$, respectively, in all energies of non-photon primaries

in a way similar to that described in Sec. 3, but with six minimal values of E_0 for each of the three curves corresponding to -30%, 0% and $+30\%$ shifts in energies of non-photon primaries. We see that the limit at $E_0 > 2 \cdot 10^{19}$ eV is uncertain by less than a few per cent while at higher energies, systematic shifts downwards reduce statistics considerably, which results in relaxing the limit. Similar uncertainties are expected for limits from other experiments shown in Fig.1. Note that the theoretical expectations presented there are also sensitive to the energy scale.

4.2. *Interaction models and simulation codes.* Our simulations were performed entirely in the CORSIKA framework, and any change in the interaction models or simulation codes, which affects either $S(600)$ or $\rho_\mu(1000)$, may affect our limit. As discussed in Ref. [6],

[1)] A 65% upper limit for energies above $1.2 \cdot 10^{20}$ eV has been claimed from the study of AGASA data [24]; however, there are problems in accounting for the difference between actual and reconstructed photon energies in that work (see Ref. [6] for a detailed discussion).

our method is quite robust with respect to the changes in the interaction models and to reasonable variations in the extrapolation of the photonuclear cross section to high energies (the values presented here were obtained for the standard parameterization of the photonuclear cross section given by the Particle Data Group [25] and implemented as default in CORSIKA).

4.3. *Primary energy spectrum.* For our limit, we used the primary photon spectrum $E_0^{-\alpha}$ for $\alpha = 2$. Change in the value of α affects the final limit on ϵ_γ through the fraction of "lost" photons, but we have found that variations of α in the interval $1 \leq \alpha \leq 3$ result in variations of ϵ_γ only within 1%.

4.4. *Width of the ρ_μ distribution.* The rare probabilities of high values of $\rho_\mu(1000)$ in the tail of the distribution for primary photons depend on the width of this distribution. The following sources contribute to this width:

- variations of the primary energy compatible with the observed $S(600)$ (larger energy corresponds to larger muon number and hence $\rho_\mu(1000)$);
- physical shower-to-shower fluctuations in muon density for a given energy (dominated by fluctuations in the first few interactions, including preshowering in the geomagnetic field);
- artificial fluctuations in $S(600)$ and $\rho_\mu(1000)$ due to thinning;
- experimental errors in $\rho_\mu(1000)$ determination.

While the first two sources are physical and are fully controlled by the simulation code, the variations of the last two may affect the results.

It has been noted in Ref. [26] that the fluctuations in $\rho_\mu(1000)$ due to thinning may affect strongly the precision of the composition studies. For the thinning parameters we use, the relative size of these fluctuations [27] is $\sim 10\%$ for $\rho_\mu(1000)$ and $\sim 5\%$ for $S(600)$. Thus with more precise simulations, the distributions of muon densities should become more narrow, which would reduce the probability of the gamma-ray interpretation of the studied events even further.

The distributions of $\rho_\mu(1000)$ we use accounted for the error in the experimental determination of this quantity. In principle, this error depends on the event quality and on the muon number itself, which is systematically lower for simulated gamma-induced showers than for the observed events. Still, we tested the stability of our limit by taking artificially high values of experimental errors in muon density: 50% instead of 25%. The limit on ϵ_γ changes by less than one per cent in that case.

5. Conclusions. To summarize, we have studied the possibility that ultra-high energy events observed by the Yakutsk array were initiated by primary photons. The use of large-area muon detectors, a unique feature of the Yakutsk experiment, together with the new analysis method [6, 7], enabled us to put stringent constraints on the gamma-ray primaries even with a relatively small set of high-quality data. An important ingredient in our study was the careful tracking of differences between the actual and reconstructed energies. We obtained upper bounds (1), (2) on the fraction ϵ_γ of primary photons, assuming an isotropic photon flux and E_0^{-2} spectrum. These limits are the strongest ones up to date; they constrain considerably the superheavy dark matter models.

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