Identification of Photons in Ultra-High Energy Cosmic Rays

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Abstract

The possibility of discerning extensive air showers initiated by ultra-high energy (UHE) photons from those induced by hadrons is studied. Two effects characteristic only for UHE photons are taken into account: LPM effect and photon conversion/cascading in the geomagnetic field. First conclusions about the possibility of identification of photons in the UHE cosmic-ray spectrum are presented and the "primary photon hypothesis" for the Fly's Eye $3.2 \cdot 10^{20}$eV event is shortly discussed.

1. Introduction

The existence of cosmic rays with energies above 10^{20}eV is experimentally proven but their nature and origin are still unknown. Theoretical models encounter large difficulties in explaining how protons or nuclei can be accelerated to such extremely high energies. There are, however, many so-called exotic scenarios considering photons as cosmic rays. Such photons could subsequently induce extensive air showers (EAS) in the Earth's atmosphere. Photon-induced showers can be distinguished from hadron-induced ones thanks to the two physical effects that are characteristic only for photons at energies above 10^{19}eV: gamma conversion with subsequent cascading in the geomagnetic field and the Landau-Pomeranchuk-Migdal (LPM) effect [5]. At energies above 10 EeV, in the presence of the geomagnetic field, a photon can convert into an e^+e^- pair before entering the atmosphere. The resultant electrons will subsequently lose their energy by magnetic bremsstrahlung. The emitted photons can convert again if their energy is high enough. In this way, instead of one high energy photon at the top of atmosphere, a number of less energetic particles, mainly photons and a few electrons, will enter the atmosphere. We will call this cascade a "preshower" since it originates and develops above the upper atmosphere, i.e. before the "ordinary" shower development in the air. A superposition of subshowers induced by the

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preshower particles should be seen by fluorescence detectors as one EAS which usually reaches its maximum much earlier than an EAS induced by a single photon of equal energy, starting at the top of atmosphere and later than a shower initiated by a hadron. Thus, the atmospheric depth of shower maximum (X_{max}) can be used as a signature of primary photon. In this paper we concentrate on the X_{max} as the most promising primary photon signature in the shower longitudinal profile. We combine CORSIKA [3] (which includes the LPM effect) with the Krakow preshower code which treats the propagation of UHE photons in magnetosphere before they enter the Earth's atmosphere.

2. Methods

Both photon conversion and magnetic bremsstrahlung depend strongly on the transverse component of the magnetic field – small variations of the field vector can cause dramatic changes of the preshower properties, and, consequently, the changes of the longitudinal development profile of the resultant EAS [4]. In our simulations we use the IGRF model [6] of the geomagnetic field and the numerical procedures [9] allowing for calculation of the field components at any given position. The photon propagation simulations are started about 5 Earth's radii above sea level. Initially, the photon trajectory is followed in steps of $dr =$ 10 km. In each step the transverse magnetic field is computed, and then the probability of conversion is found using Eq. (1):

$$p_{conv}(r) = 1 - \exp[-\alpha(\chi(r))dr] \simeq \alpha(\chi(r))dr \tag{1}$$

where $\alpha(\chi) = 0.5(\alpha_{fs} m_e c/\hbar)(B_\perp/B_{cr})T(\chi)$, $\chi \equiv 0.5(h\nu/m_e c^2)(B_\perp/B_{cr})$, α_{fs} is the fine structure constant, $B_\perp$ is the magnetic field component transverse to the direction of photon motion, $B_{cr} \equiv m_e^2 c^3/e\hbar = 4.414 \cdot 10^{13}$ G, and $T(\chi)$ is the magnetic pair production function which is negligible if $\chi \ll 1$, has a maximum around $\chi = 5$ and then decreases slowly to zero [2, 4].

If conversion takes place, the photon creates an e^+e^- pair; the e^{+-} particles begin to emit bremsstrahlung. The probability of emitting a photon by a single electron over a small distance dr is calculated in every 1 km with use of Eq. (2):

$$p_{brem}(B_\perp, E, h\nu, dr) = dr \int_0^E I(B_\perp, E, h\nu) \frac{d(h\nu)}{h\nu} \tag{2}$$

where $I(B_\perp, E, h\nu)$ is the spectral distribution of radiated energy, E is the electron initial energy and $h\nu$ is the energy of the emitted bremsstrahlung photon [8, 4]. Once a photon is emitted, its energy is assigned according to the probability distribution given by Eq. (2), and the energy of the radiating electron is diminished respectively. Bremsstrahlung photons of energies lower than 10^{12}eV have a very small influence on the air shower evolution and hence they can be

Table 1. X_{max} and RMS values for photon-induced showers of two different primary energies and arrival directions.

E_0[eV]	direction	fraction of converted	$\langle X_{max} \rangle$ [g/cm^2]
10^{20}	weak $B_\perp$	1/50	1125 ± 105
	strong $B_\perp$	48/50	920 ± 55
10^{21}	weak $B_\perp$	50/50	1025 ± 45
	strong $B_\perp$	50/50	945 ± 15

neglected. The preshower simulations are finished when the top of atmosphere is reached. Then all preshower particles are passed to CORSIKA. The resultant EAS is simulated by CORSIKA as a superposition of subshowers initiated by the preshower particles.

3. First Results for the Pierre Auger Southern Site

In Table 1 we compare X_{max} and RMS of X_{max} for simulated photon-induced showers for two different primary energies and arrival directions. The results presented here were obtained for the Southern Pierre Auger Observatory (PAO) in Malargüe, Argentina (35.2°S, 69.2°W) [7], but other geographical positions can be easily adopted. Here the strong $B_\perp$ direction is defined as $\theta = 53°$, $\phi = 177°$ and weak $B_\perp$ as $\theta = 53°$, $\phi = 357°$ in the local frame at Malargüe with the azimuth increasing in the counter-clockwise direction beginning from the geographical North. In all cases the shower maxima are well inside the atmosphere at the Southern PAO with a slant depth of 1450 g/cm^2 for a zenith angle $\theta = 53°$. For proton-induced EAS a X_{max} value of 820 ± 60 g/cm^2 for 10^{20}eV and 870 ± 50 g/cm^2 for 10^{21}eV is expected.

For $E_0 = 10^{20}$eV and weak $B_\perp$, almost all photons remain unconverted when entering atmosphere, which results in large $\langle X_{max} \rangle$ and large fluctuations due to the LPM effect. A comparison with hadronic primaries allows for the conclusion that unconverted primary photons should be well distinguishable from p and Fe on an event-by-event basis. At the primary energy of 10^{21}eV all photons convert, whatever the arrival direction. We still see the directional dependence of $\langle X_{max} \rangle$, but it is not as strong as previously. The fluctuations of X_{max} in this case are significantly lower (by about a factor of 3) than for 10^{20}eV primaries. Table 1 shows that at 10^{21}eV it is more difficult to distinguish a single photon primary from a proton one on the basis of X_{max} value. Since in the Auger Experiment we don't expect large statistics of such events, it might be a challenge to notice the azimuthal asymmetry of X_{max} or the decrease of RMS fluctuations. Studies of the elongation rates for different arrival directions seem to be promising. From Table 1 we find out that at Malargüe, for the strong $B_\perp$ direction, the elongation rate of photon-induced showers between 10^{20}eV and 10^{21}eV is much less than 50-60 g/cm^2 expected for proton or iron showers. For the weak $B_\perp$ we even have a *negative* elongation rate. This is because the preshowering effect for photons at 10^{21}eV splits the initial energy into energies less than 10^{20}eV and at this energy level, for the weak $B_\perp$ direction, almost all the primary photons remain unconverted and they induce air showers with deeper X_{max}. Lower than expected or negative elongation rates should be an additional good signature of photon showers, provided a sufficient statistics is available.

4. Fly's Eye Highest Energy Event

The methods and tools described above were applied to real data of the highest-energy shower ever detected – a cosmic ray event recorded by the Fly's Eye Experiment in 1991 [1]. To estimate the probability that the recorded EAS was induced by a photon, we used our preshower+CORSIKA program to simulate 250 shower profiles with the parameters of the event: primary photon with initial energy $E_0 = 3.2 \cdot 10^{20}$eV, zenith angle $\theta = 43.9°$, azimuth $\phi = 32.0°$ (counter-clockwise from East) and for the geographical location of the detector (40°N, 113°W). The experimental value of the shower maximum is $X_{max} = 815^{+60}_{-53}$ g/cm^2 [1], while from the simulations we get an average value of $X_{max}(sim) = 925 \pm 25$ g/cm^2. For each simulated profile a χ^2 value and the probability that the profile fits the data were computed. The average probability that the record EAS detected by Fly's Eye was initiated by a photon is about 1-2% whilst the probability for the profile closest to the data is about 40%. These preliminary results do not allow to exclude a photon as primary particle.

Acknowledgements. This work was partially supported in Poland by the KBN grants No. PBZ KBN 054/P03/2001 and 2P03B 11024 and in Germany by the BMBF grant No. POL 99/013.

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