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Positron production due to interaction of cosmological background photons

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Abstract. The interaction of photons of the cosmological background radiation with producing electron-positron pairs is considered. It is shown that main input in positron production is given by interaction of cosmological gamma-ray background photons with photons of extragalactic background light, although taking into account the interaction of cosmological gamma-ray background photons with cosmological ultraviolet background photons may substantially increase the pair production rate.

Keywords: positron, photon, cosmology radiation background

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Генерация позитронов при взаимодействии фотонов космологического фона

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Аннотация. Рассматривается взаимодействие фотонов космологического фонового излучения с рождением пар. Показано, что основной вклад в рождение пар дает взаимодействие фотонов космологического гамма-фона с фотонами внегалактического оптического излучения, хотя учет взаимодействия фотонов космологического гамма-фона с фотонами космологического ультрафиолетового фона может существенно увеличить темп рождения позитронов.

Ключевые слова: позитрон, фотон, космологическое фоновое излучение

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Introduction

The cosmological background radiation (CB) is homogeneous, isotropic radiation that fills all Universe. The main component of CB is cosmological microwave background radiation (CMB) which is a relict of the epoch of reionization and it gives us a knowledge about process in this epoch [1]. The second most important [1] component of CB is optical extragalactic background light (EBL). It is mainly created by radiation of stars and consequently it contains a history of star formation [1–3]. The cosmological gamma-ray background radiation (CGB) is mainly created by supernovae and active galactic nuclei and hence it gives us an information about evolution of activity of galactic nuclei and star formation rate [1, 4]. The cosmological X-ray background radiation (CXB) is mainly created by radiation of accretion disks in the galactic nuclei [1, 5]. And the cosmological ultraviolet background radiation (CUB) is mainly radiated by hot young stars and interstellar nebulae [1] and consequently gives us an information about evolution of these objects. In this paper we consider the production of electron-positron pairs due to interaction of high energetic but not numerous CGB photons with numerous but low energetic EBL and CUB photons.

Photon-photon interaction

Let us consider the interaction of two photons producing electron-positron pair. The cross-section σ of this process is given by the following expression [6]:

$$\sigma = \sigma(s) = \frac{\pi}{2} r_e^2 \cdot \left(1 - v^2\right) \times \\ \times \left(\left(3 - v^2\right) \ln\left(\frac{1+v}{1-v}\right) - 2v\left(2 - v^2\right) \right) \cdot h\left(s-1\right), \tag{1}$$

where $r_e = e^2/mc^2$ is classical electron radius, m is the rest mass of electron, $h(x)$ is Heaviside function ($h(x) = 1$ at $x > 0$ and $h(x) = 0$ at $x < 0$),

$$v = \sqrt{1 - 1/s} \text{ and } s = \frac{1}{2} \frac{\varepsilon_1 \varepsilon_2}{m^2 c^4} \left(1 - \cos\Psi\right), \tag{2}$$

ε_1 and ε_2 are photons energies and Ψ is angle between the momenta of the two photons, see Fig. 1. In the case of isotropic photon distribution the pair production rate is given by the following expression:

$$Q_{tot} = \int_0^{+\infty} Q \cdot d\varepsilon_1 d\varepsilon_2 = \int_0^{+\infty} c\Sigma\left(\frac{\varepsilon_1 \cdot \varepsilon_2}{m^2 c^4}\right) \cdot \frac{dn_1}{d\varepsilon_1}(\varepsilon_1) \cdot \frac{dn_2}{d\varepsilon_2}(\varepsilon_2) \cdot d\varepsilon_1 d\varepsilon_2, \tag{3}$$

where Q_{tot} is total number of pairs produced in 1 cm^3 per 1 s, $dn_i = \frac{dn_i}{d\varepsilon_i}(\varepsilon_i) \cdot \mathrm{d}\varepsilon_i$ is the number density of photons of kind i with energy $\varepsilon_i \in d\varepsilon_i$, $i = 1, 2$ and functions Q and $\Sigma(s)$ are defined as

$$Q = c\Sigma\left(\frac{\varepsilon_1 \cdot \varepsilon_2}{m^2 c^4}\right) \cdot \frac{dn_1}{d\varepsilon_1}(\varepsilon_1) \cdot \frac{dn_2}{d\varepsilon_2}(\varepsilon_2), \text{ and } \Sigma(s) = \frac{2}{s^2} \cdot \int_1^s \sigma(\tilde{s}) \cdot d\tilde{s}, \tag{4}$$

so $dN = Q \cdot d\varepsilon_1 d\varepsilon_2$ is number of pairs produced in 1 cm^3 per 1 s by interaction of photons with energies ε_1 and ε_2, which lies in intervals $d\varepsilon_1$ and $d\varepsilon_2$correspondingly and $\Sigma(s)$ may be considered as averaged cross-section. The graphics of functions $\sigma(s)$ and $\Sigma(s)$ are presented in left panel of Fig. 2.

In the case of "power-law" photon spectrum $\frac{dn_1}{d\varepsilon_1}(\varepsilon_1) = \mathrm{K}\,\varepsilon_1^{-\gamma_1}\cdot h\left(\varepsilon_1 - \varepsilon_1^{\min}\right)$ and $\frac{dn_2}{d\varepsilon_2}(\varepsilon_2) = \mathrm{K}\,\varepsilon_2^{-\gamma_2}\cdot h\left(\varepsilon_2^{\max} - \varepsilon_2\right)\cdot h\left(\varepsilon_2 - \varepsilon_2^{\min}\right)$ and with the assumptions $\gamma_1 > 2$ and $\varepsilon_1^{\min}\cdot\varepsilon_2^{\max} \le m^2c^4$ the total pair production rate is equal to

$$Q_{tot} = c\Sigma_{\gamma_1}\cdot n_1\cdot n_2\cdot 2\cdot\frac{\gamma_1-1}{\gamma_1+1}\cdot\frac{1-\gamma_2}{\gamma_1-\gamma_2}\cdot\frac{1-r_2^{\gamma_1-\gamma_2}}{1-r_2^{1-\gamma_2}}\cdot\left(\frac{\varepsilon_1^{\min}\cdot\varepsilon_2^{\max}}{m^2c^4}\right)^{\gamma_1-1}, \tag{5}$$

where $r_2 = \varepsilon_2^{\min}/\varepsilon_2^{\max}$, $\Sigma_\gamma = \int_1^{+\infty}\sigma(s)\cdot s^{-\gamma}\cdot ds$ and $n_i = \int_0^{+\infty}\frac{dn_i}{d\varepsilon_i}(\varepsilon_i)\cdot d\varepsilon_i$ is the number density of photons of kind i, $i = 1, 2$. The dependence of $\Sigma(s)$ on γ is presented on right panel of Fig. 2.

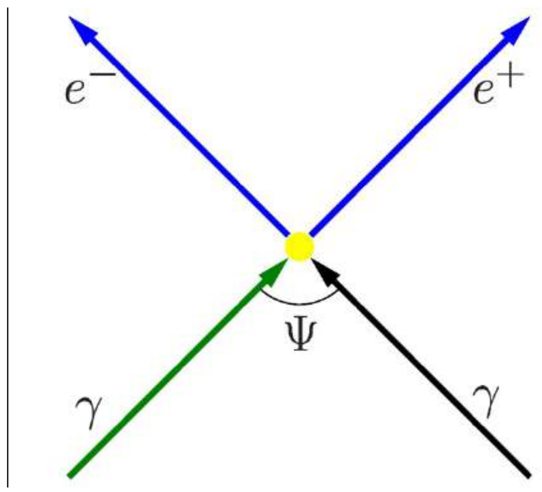

Fig. 1. Sketch to illustrate the interaction of two photons producing electron-positron pair

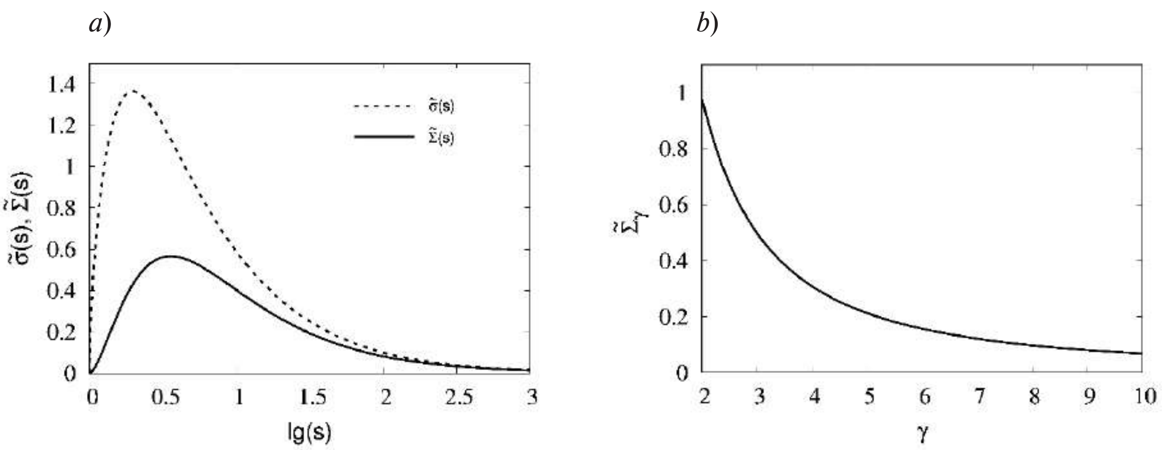

Fig. 2. Graphs of functions $\sigma(s)$ and $\Sigma(s)$ are presented on left panel (*a*).
Dashed line corresponds to normalized cross-section of pair production $\tilde{\sigma}(s) = 2\cdot\sigma(s)/(\pi r_e^2)$
and solid line corresponds to normalized averaged cross-section $\tilde{\Sigma}(s) = 2\cdot\Sigma(s)/(\pi r_e^2)$.
The dependence of $\tilde{\Sigma}_\gamma = 2\cdot\Sigma_\gamma/(\pi r_e^2)$ on parameter γ is presented on right panel (*b*)

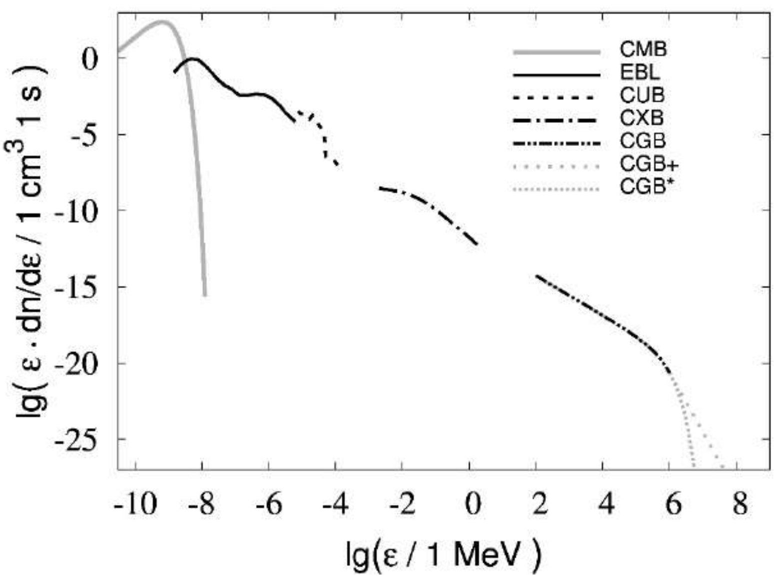

Fig. 3. CB spectrum used in calculation are presented. The CMB spectrum is shown with the solid gray line. The EBL spectrum taken from [3] is shown with the solid black line, the upper limit on the CUB spectrum taken from [1] is shown with the dashed black line, the CXB spectrum taken from [5] is shown with the dot-dashed black line and the CGB spectrum taken from [4] is shown with the double dot-dashed black line. The extrapolations of the CGB spectrum up to 100 TeV are shown with the dotted gray lines

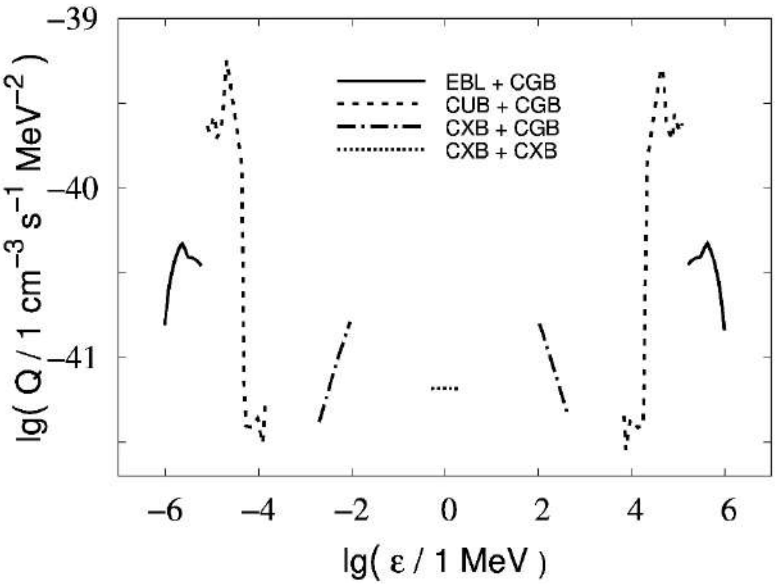

Fig. 4. The dependence of pair production rate Q (in units of $1 \mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-2}$) on photon energy ε is presented. The solid line corresponds to the interaction of the CGB photons with the EBL photons, the dashed line corresponds to the interaction of the CGB photons with the CUB photons, the dot-dashed line corresponds to the interaction of the CGB photons with the CXB photons and the dotted line corresponds to the interaction of the CXB photons with itself

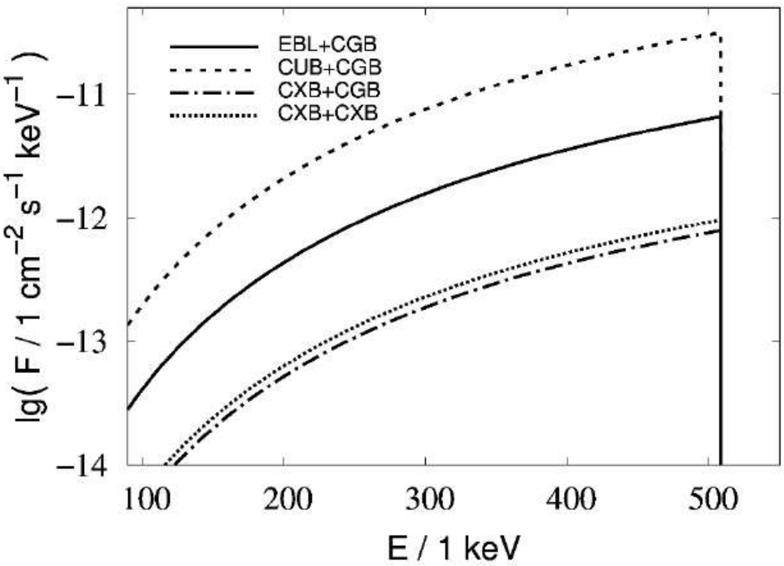

Fig. 5. Here F is annihilation photon flux (at z =0) in units of 1 cm^{-2} s^{-1} keV^{-1}, E is annihilation photon energy. The lines mean the same as in Fig. 4

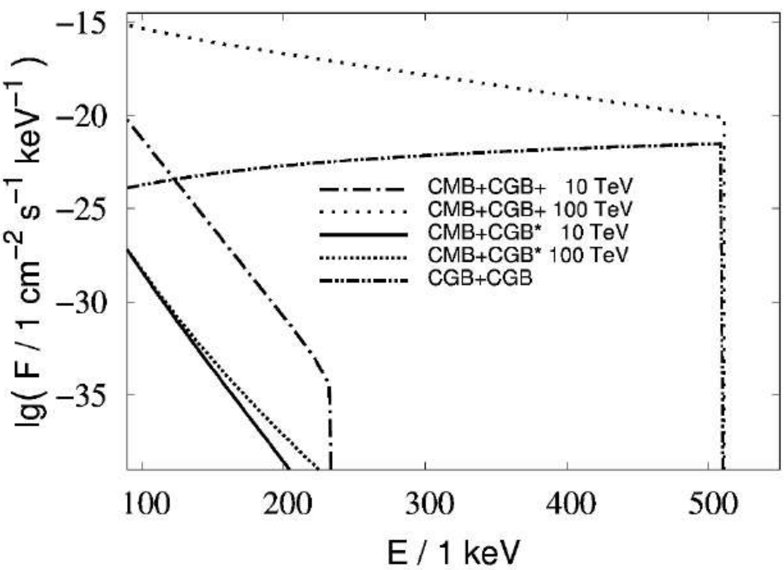

Fig. 6. Same as Fig. 5, but the case of the interaction of the CMB photons with the CGB photons is presented. The solid and the dot-dashed lines correspond to extrapolation of the CGB spectrum up to 10 TeV, the dotted lines correspond to extrapolation of the CGB spectrum up to 100 TeV. The double dot-dashed line corresponds to the interaction of the CGB photons with itself

Results

We have considered the interaction of CGB photons with CXB and EBL photons. Spectrum of CGB, CXB and EBL photons used in calculation taken from [4], [5] and [3] correspondingly are presented in Fig. 3. The resulting pair production rate Q_{tot} values are presented in table 1. In order to estimate pair production rate due to the interaction of CGB photons with CUB photons we also consider the case when CUB photons spectra coincides with its upper limits taken from [1]. In this paper we neglect the interaction of CGB photons with itself because of it gives negligible pair production rate.

Table 1

Pair production rate Q_{tot} in units of 1 cm^{-3} s^{-1}.

	EBL+CGB	CUB+CGB	CXB+CGB	CGB+CGB	CXB+CXB
Q_{tot}	$5.0 \cdot 10^{-37}$	$2.4 \cdot 10^{-36}$	$6.0 \cdot 10^{-38}$	$2.3 \cdot 10^{-47}$	$7.3 \cdot 10^{-38}$

In calculation of the pair production rate Q_{tot} the EBL spectrum is taken in range 1.5 meV—3 eV, the CXB spectrum is taken in range 2 keV-1.5 MeV, the CGB spectrum is taken in range 100 MeV—1 TeV and the upper limit of the CUB spectrum is taken in range 7.5—120 eV

The dependence of pair production rate Q on photon energies is presented in Fig. 4. Here we assume that photon energies are related as $\varepsilon_1 \cdot \varepsilon_2 = \varepsilon_0^2$ where ε_1 is the energy of EBL, CUB or CXB photon correspondingly, ε_2 is energy of CGB photon and $\varepsilon_0 \approx 1$ MeV. A such value of ε_0 corresponds to the maximum of averaged cross-section Σ. This figure shows that the interaction of CGB photons with EBL photons gives main input in electron-positron pairs production although the taking into account the interaction of CGB photons with CUB photons may substantially increase the pair production rate.

The positrons created due to these interactions will slow down and annihilate later producing two or three photons. In this paper we, for simplicity, assume that all positrons annihilate immediately and neglect of annihilation photon absorption. Also we neglect the input of three photon annihilation and suppose that CB spectrum do not depend on red shift z. In this case the observed (at $z = 0$) distribution of annihilation photons may be written as

$$\frac{dN}{dVdEd\Omega} = \frac{Q_{tot}}{4\pi} \cdot \frac{1}{H_0} \cdot \frac{1}{mc^2} \cdot \left(\frac{E}{mc^2}\right)^2 \cdot \frac{1}{\tilde{F}(mc^2/E)} \cdot h\left(mc^2 - E\right), \tag{6}$$

where E is energy of annihilation photon (at $z = 0$), $E = mc^2/(1+z)$ and $H_0 = 67.8$ km s^{-1} Mpc^{-1} is Hubble constant at present epoch ($z = 0$) [7]. In case of standard ΛCDM-cosmological model (at $z \ll z_{eq}$ where $z_{eq} \approx 3365$ is the redshift of the transition from a radiation-dominated to a matter-dominated Universe) the function $\tilde{F}(x)$ is equal to $\tilde{F}(x) = \sqrt{\Omega_\Lambda + \Omega_M \cdot x^3}$, where coefficients $\Omega_\Lambda = 0.692$ and $\Omega_M = 0.308$ describe relative fractions of dark energy and dark matter correspondingly [7]. The resulting profile of annihilation line is presented in figure 5. The width of this “line” is very large $\Delta E \sim 100 - 150$ keV and the line flux is about $F \sim 10^{-12}$ cm^{-2} s^{-1} keV^{-1} without taking into account the interaction of CGB and CUB photons and may achieve $F \sim 10^{-11}$ cm^{-2} s^{-1} keV^{-1} with taking into account this interaction.

We also consider the interaction of photons of the extrapolated CGB spectrum with the CMB photons. The resulted profiles of annihilation line are presented in figure 6. In calculation only the CMB photons with frequencies $\nu \leq 3$ THz are taken in account because of the EBL radiation has already totally dominated at $\nu \sim 3$ THz, see Fig. 3. We consider two variants of extrapolation. The CGB+ spectrum corresponds to power law extrapolation by using last two point, the CGB* spectrum corresponds to extrapolation by using approximation formula $\varepsilon \cdot \frac{dn}{d\varepsilon}(\varepsilon) = I_{100} \cdot \left(\frac{\varepsilon}{100MeV}\right)^{-\gamma+1} \cdot \exp\left(-\frac{\varepsilon}{\varepsilon_{cut}}\right)$ where $\gamma \approx 2.3$, $I_{100} \approx 5.4 \cdot 10^{-14}$ cm^{-3} and $\varepsilon_{cut} \approx 366$ GeV [4], see Fig. 3. The two cases of extrapolation up to 10 TeV and up to 100 TeV correspondingly are considered. Also the profile of annihilation line due to the interaction of the CGB photons with itself is presented in figure 6. It is easy to see that the positron production due to the interaction of the CMB photons with the CGB photons is comparable to the production by the interaction of the CGB photons with itself. So its input to the total positron production is negligible too. The cutoff of annihilation line in the case of the CGB+ spectrum extrapolated up to 10 TeV at $E \approx 230$ keV is artificial and is related to our restriction on the considered CMB photons energies $\nu \leq 3$ THz.

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