Ultrahigh energy gamma rays as carriers of cosmological information

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The possibility of testing various cosmological hypotheses by means of breaks in the spectra of gamma rays from extragalactic objects in the region of ultrahigh energies ($\sim 10^{12}$–10^{14} eV) is discussed.

1. INTRODUCTION

One of the most important and still open problems of modern cosmology is that of the creation and evolution of the universe. The observational material on which modern cosmological models are based is very limited: the recession of the galaxies (Hubble expansion), the abundances of the elements; and the existence of the fossil microwave background. The importance of the last discovery for the model of a hot expanding universe (Big Bang) must be particularly stressed. This model predicted the existence of background radiation, a fossil of the Big Bang, and also explained the abundances of the simplest nuclei in the universe (see, for example, Ref. 1). It was the discovery of the microwave background that was evidently responsible for the intensive development of "hot universe" models. As a result, other cosmological models were overshadowed and at the present time are hardly discussed (see, however, Ref. 2). At the same time, it should be noted that the ratio observations of the microwave background give information about it only near the Earth, i.e., at the contemporary epoch. But a distinctive feature of all modifications of the hot model is the strong evolution of the fossil radiation in time. It is obvious that experimental proof of evolution of this radiation, i.e., probing of it in the distant past, would be a direct verification of the Big Bang hypothesis.

Such information can be obtained only by studying particles that interacted with the radiation in remote epochs. It is obvious that to be such information carriers the particles must, first, interact effectively with the radiation and, second, make it possible to fix the interaction epoch unambiguously. The last requirement reduces to a tying of these particles to definite objects with large red shift ($z_0 \gtrsim 1$) and thus to the requirement that they propagate rectilinearly in the intergalactic medium. These requirements are met only by "tagged" γ rays of ultrahigh energies, i.e., photons with $E_\gamma \gg 10^{13}$ eV emitted by discrete sources at cosmological distances. The main interaction channel of γ rays with energy $E_\gamma 10^{21}$ eV with the background radiation is the $\gamma + \gamma \to e^+e^-$ reaction.[3–6] It is remarkable that because the gas density in the intergalactic medium is low this reaction is practically the only one ($\langle l\rho\rangle \lesssim c\rho_{cr}/H_0 \sim 3H_0c/8\pi G \sim 0.1$ g/cm^2), and therefore the information reaches the observer without significant distortion.

2. INTERACTION OF γ RAYS WITH THE BACKGROUND RADIATION

Two colliding photons with energies E_γ and ε can produce a pair (e^+,e^-) provided

$$E_\gamma \geqslant 2m_e^2c^4/\varepsilon(1-\cos\theta), \tag{1}$$

where θ is the collision angle, and m_e is the electron rest mass.

When γ rays pass through an isotropic field of photons with characteristic energy $\bar{\varepsilon}$, the photoproduction cross section, averaged over all angles, depends only on the parameter $b = E_\gamma\bar{\varepsilon}/m_e^2c^4$:

$$\langle\sigma\rangle = \frac{1}{2}\int_{-1}^{1-2/b}(1-\cos\theta)\sigma_0 d\cos\theta, \tag{2}$$

where σ_0 is the total cross section of (e^+,e^-) pair production. Beginning at the threshold value $b = 1$, the value of $\langle\sigma\rangle$ rapidly increases $[\propto (b-1)^{3/2}]$, reaching a maximum at $b = 3$, after which it slowly decreases, following the law $b^{-1}\ln b$.[4]

The mean free path λ of γ rays in a black-body photon field with temperature T_r was calculated in Ref. 4:

$$\lambda^{-1} = \frac{\alpha^2}{\pi\Lambda}\left(\frac{kT_r}{m_ec^2}\right)^3 f(\nu), \tag{3}$$

where $\alpha = 1/137$, $\Lambda = \hbar/m_ec \approx 3.86\times10^{-11}$ cm. The function $f(\nu)$, where $\nu = (m_ec^2)^2/kT_rE_\gamma$, was tabulated in Ref. 4. It has a maximum $f_{\max} \sim 1$ at $\nu \sim 1$. In the limit $\nu \ll 1$, the function $f(\nu)$ can be expressed in analytic form[7]:

$$f(\nu) = {}^1/_3\pi^2\nu\ln(0{,}467/\nu) + \nu^2[{}^1/_3\ln^3(1/\nu) + (2\ln 2-1)\ln^2(1/\nu) + O(\ln\nu)]. \tag{4}$$

In the opposite limit, $\nu \gg 1$, the analytic expression given for $f(\nu)$ in Ref. 4 is incorrect; since it is this region of ν values in which we shall be interested, we give here the corrected expression.

Expanding the total cross section in (2) in a series with respect to the parameter $(b-1)^{1/2}$ and integrating over the angles, we readily find for the averaged cross section near the reaction threshold $(b-1 \ll 1)$

$$\langle\sigma\rangle = (4\pi r_0^2/3b^2)[(b-1)^{3/2} + 0.3(b-1)^{5/2}], \tag{5}$$

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where $r_0 = e^2/m_e c^2$ is the classical electron radius. Calculating the mean free path of γ rays with energy $E_\gamma \ll (m_e c^2)^2/kT_r$ ($\nu \ll 1$), we obtain for the function $f(\nu)$

$$f(\nu) = (1+3/4\nu)(\pi\nu)^{1/2} e^{-\nu}. \quad (6)$$

It follows from (3) that the mean free path of γ rays in the background radiation field with temperature $T = 2.7$ °K is minimal at $E_\gamma \sim 10^{15}$ eV ($\nu \sim 1$) and is $\lambda(\sim 10^{15}$ eV) ≈ 8 kpc. For γ rays of both lower and higher energies, the mean free path is greater, but for different reasons. A weak growth, proportional to $E_\gamma \ln^{-1} E_\gamma$ for $E_\gamma \gg 10^{15}$ eV, is due to the decreasing nature of the cross section for $b \gg 1$. The sharp increase in λ when $E_\gamma \ll 10^{15}$ eV is due to the pair production threshold: The γ rays interact only with the Wien tail of the background radiation. For this, there is a simple dependence of λ on E_γ:

$$\lambda \approx 1.8 \cdot 10^{-2} [(1+3/4\nu)\nu^{1/2}]^{-1} e^{\nu} \text{ Mpc}. \quad (7)$$

It is easy to show that for $E_\gamma \sim (0.7\text{–}1) \times 10^{14}$ eV the value of λ varies in the wide interval 10^2–10^4 Mpc, which corresponds to the distances to quasars.

We note however that this expression has been obtained for the isothermal Planck distribution. But for cosmological distances an important role may be played by evolution effects, especially the variation in the temperature of the background radiation in the Big Bang model. We obtain corresponding expressions for the mean free path taking into account the evolution of the background radiation.

Suppose that at epoch z there are N photons moving in the direction of the observer with energy $E_{\gamma z} = E_\gamma(1+z)$. The rate at which these photons are knocked out of the beam is determined by the expression

$$\frac{dN}{dt'} = -Nc \int_{\omega_0(z)}^{\infty} \langle\sigma\rangle \frac{dn(\omega, z)}{d\omega} d\omega, \quad (8)$$

where $dn(\omega,z)$ is the density of the background radiation at the epoch z.

Under the assumption of a purely Planck distribution of the photons,

$$dn(\omega, z) = \frac{\omega^2 \, d\omega}{\pi^2 \hbar^3 c^3 [\exp(\omega/kT(z)) - 1]} \quad (9)$$

and

$$T(z) = T_0(1+z), \quad (10)$$

where $T_0 = 2.7$ °K is the observed temperature of the radiation at the present epoch, E_γ is the energy of a detected γ ray, and

$$\omega_0(z) = m_e^2 c^4 / E_\gamma(1+z). \quad (11)$$

The reaction rate (8) has been written down for an expanding system. Going over to the laboratory coordinate system (of the observer), we must take into account the relativistic time contraction:

$$\frac{dt'}{dt} = (1-\beta^2)^{-1/2} = \frac{1+(1+z)^2 g^2}{2(1+z)g} \equiv \varphi(z), \quad (12)$$

where

$$g = 1 + \frac{\Omega}{4}(1+z)^3 H_0^2 t^2(z), \qquad H_0 t(z) = \int_0^z \frac{dx}{(1+x)^2(1+\Omega x)^{1/2}}, \quad (13)$$

$\Omega = \rho/\rho_{cr}$, H_0 is Hubble's constant, and $\rho_{cr} = 3H_0^2/8\pi G \approx 6 \times 10^{-30}$ g/cm^3 (for $H_0 = 55$ km · sec^{-1} · Mpc^{-1}) is the critical density (see, for example, Ref. 1). Further, expressing dt in terms of dz and integrating over ω and z (from 0 to z_0), we finally obtain

$$N = N_0 \exp[-\tau(E_{\gamma 0}, z_0)], \quad (14)$$

where

$$\tau(E_{\gamma 0}, z_0) \equiv A\nu_0^{1/2} \int_0^{z_0} \varphi(z) \frac{\exp[-\nu_0/(1+z)^2]}{(1+\Omega z)^{1/2}} dz$$

$$\approx \frac{A}{2} \frac{(1+z_0)^3}{(1+\Omega z_0)^{1/2}} \varphi(z_0) \nu_0^{-1/2} \exp\left[-\frac{\nu_0}{(1+z_0)^2}\right] \left[1 + O\left(\frac{1}{\nu_0}\right)\right], \quad (15)$$

$$A = \Gamma_0^2 (kT_0)^3 / \pi^{1/2} \hbar^3 c^2 H_0, \qquad \nu_0 \equiv m_e^2 c^4 / kT_0 E_{\gamma 0}. \quad (16)$$

As will be seen from what follows, $\nu \gg 1$ in the region in which we are interested, and therefore the accuracy of the expression (15) is perfectly acceptable if $\nu[1 - (1+z_0)^{-2}] > 3$. In the limit $z_0 \to 0$, we can obtain from the condition $\tau(E_{\gamma 0}, z_0) = 1$ an expression for the γ-ray mean free path that is identical to (3) and (6), bearing in mind that $R \approx cz/H_0$ for $z_0 \ll 1$.

Hitherto, we have assumed that the background radiation is described exactly by the Planck distribution. In fact, the observational data, which agree well with the Planck distribution, refer only to the region of wavelengths $\lambda > 1$ mm. For shorter wavelengths, there are as yet no reliable data. However, there has been much discussion in the literature of a possible deviation from the Planck distribution in the submillimeter range (see, for example, Ref. 8). In particular, such a deviation could be due to Comptonization of the background radiation if there was a late release of energy (at $z \lesssim 10^4$). In this case, the spectrum of the background radiation is described by the expression[1,8]

$$n(x, y) = \frac{\exp(-9y/4)}{(4\pi y)^{1/2}} \int_0^\infty \frac{1}{e^{x\xi} - 1} \xi^{(1/2 - \ln \xi/4y)} d\xi, \quad (17)$$

where $x = \omega/kT_0$, and the Comptonization parameter is

$$y = \int \frac{kT_e(t)}{m_e c^2} \sigma_T c N_e(t) \, dt. \quad (18)$$

The analysis made by Field and Perrenod[9] shows that the existing observational data allow $y \lesssim 0.055$. Even at such small values of the Comptonization parameter, the deviations from the purely Planck distribution ($y = 0$) in the Wien part of the spectrum become appreciable, and this leads to a significant shift in the expected position of the break in the spectra of ultrahigh energy γ rays.

3. POSSIBLE COSMOLOGICAL TESTS

Suppose a source at distance R emits γ rays with spectrum $N_0(E_\gamma)$ that extends into the region of ultrahigh energies. As a result of interaction with the background radiation, the γ rays reach the observer with a distorted spectrum:

$$N(E_\gamma) = N_0(E_\gamma)\exp[-\tau_R(E_\gamma)], \qquad (19)$$

where $\tau_R(E_\gamma)$ is the optical thickness with respect to (e^+, e^-) pair production in photon-photon collisions.

As was noted above, the mean free path [corresponding to the condition $\tau(E_\gamma) = 1$] is minimal for γ rays with energy $E_\gamma \sim 10^{15}$ eV and is ~ 8 kpc. The intergalactic medium is therefore opaque for photons with $E_\gamma \geqslant 10^{15}$ eV. This was the reason why the detection of γ rays with $E_\gamma \geqslant 10^{15}$ eV yielded the first observational evidence for the existence of sources of ultrahigh energy cosmic rays of galactic origin.[10]

But in the case of photons of lower energies, the mean free path λ increases sharply because of the threshold nature of the reaction, which means that the γ rays can interact only with the Wien tail of the background radiation. As follows from the expression (8), a variation of E_γ in the range of energies $(0.7\text{–}1.4)\times 10^{14}$ eV corresponds to variation of the mean free path in the wide range 10^4–10^1 Mpc. Thus, in a relatively narrow energy region one must expect a sharp break in the spectra of extragalactic sources. More precisely, the position of the break is determined by the distance R to the source, the shape of the spectrum of the background radiation in the submillimeter range, and the evolution of the radiation in time. This circumstance provides a unique possibility for solving a number of cosmological problems.

A number of terrestrial facilities are currently used successfully to study primary γ rays in the energy range 10^{11}–10^{13} eV (detection of the Cherenkov radiation of extensive air showers) and $E_\gamma \geqslant 5\times 10^{14}$ eV (through the search for extensive air showers with anomalously low muon content). It is noteworthy that both methods can in principle be extended to detection in the range 10^{13}–10^{14} eV. This offers hope that such a possibility can be realized (at least partly) in the not too distant future. Since the shape of the expected γ-ray spectrum is determined by several independent factors, it is expedient to make investigations in the following stages.

3.1. Investigations of extragalactic objects with small values of z_0

a) Objects with known distances

For known distance R to a source with small value of z_0, the optical thickness $\tau_R(E_\gamma)$ and, therefore, the expected position of the break in the spectrum are determined solely by the shape of the spectrum of the background radiation in the submillimeter range. It is therefore possible to probe directly the radiation in this as yet uninvestigated region. As noted above, there are above all possibilities here of deviation from the Planck distribution due to Comptonization of the radiation in the event of a late release of energy. In this case, the spectrum of the background radiation is described by the expression (17).

Figure 1 shows the expected spectra of γ rays from a source at distance $R = 5$ Mpc, the distance to the nearest radio galaxy Centaurus A. The point of the break defined in

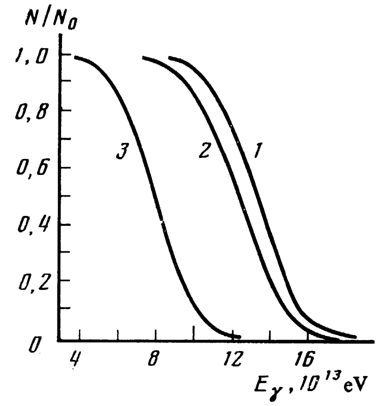

FIG. 1. Expected spectra N/N_0 of γ rays from a source at distance $R = 5$ Mpc for different values of the Comptonization parameter y: 1) $y = 0$, 2) $y = 0.01$, 3) $y = 0.05$.

what follows as the energy E_c at which $N/N_0 = e^{-1}$, is shifted significantly to lower energies: from $E_c \approx 1.4\times 10^{14}$ eV at $y = 0$ to $E_c \approx 8\times 10^{13}$ eV at $y = 0.05$. It can be seen that determination of y with accuracy $\Delta y = 0.01$ can be achieved if the energy resolution of the detecting apparatus is $\sim 10\%$.

It should be pointed out here that deviations from the Planck distribution due to other causes are also possible. For example, it is possible that there is a hump in the region of $\lambda \approx 0.25$ mm associated with superposition on the background radiation spectrum of recombination radiation at $z \sim 10^3$.[11,12] Direct measurements of the background radiation in this region by probes and spacecraft are subject to not only methodological difficulties (due to the presence of a high local background) but also, more importantly, may be in principle impossible because of a possible background produced by emission of interstellar dust[13] and gas.[14] It is obvious that an effect of these factors is precluded in the method proposed here.

To recover the shape of the background radiation spectrum in the submillimeter range, it is necessary to investigate the radition of γ sources at well-known distances. Besides the already mentioned Centaurus A, suitable sources for this task could also be the active galaxies NGC 4151, MCG 8-11-11, and 3C 120, from which ultrahigh energy γ rays are expected on the basis of modern ideas. For the extension of the region of probing of the background radiation to shorter wavelengths, it is necessary to investigate more distant sources, i.e., quasars. However, it is first necessary to demonstrate that quasars are indeed at cosmological distances.

b) Determination of distances to quasars

Discovered 20 years ago, quasars still remain to a high degree mysterious objects. Although the majority of astronomers are emphatic that the observed red shifts in the optical spectra of the quasars have a cosmological origin, there is still no direct refutation of the arguments for a local origin of these objects (see, for example, Ref. 15). The main obstacle to explanation of the nature of these remarkable objects is still the absence of even one model-independent method of determining the distances to them.

Above, we discussed the possibility of recovering the background radiation spectrum from the expected break in the spectrum of γ rays from sources with well-known distance to them. But if we can measure with sufficient accuracy the background radiation spectrum in the submillimeter range, it becomes possible to determine the distances to extragalactic sources without any model assumptions:

$$R=\lambda(E_c),$$

where E_c is the observed point of the break, and λ is the mean free path. In the case of a purely Planck distribution and small z_0, the mean free path is given by the expression (7).

Unfortunately, because of the strong dependence of λ on E_γ, this problem is very complicated from the experimental point of view. The error in the determination of R for corresponding break energy E_c in the region of energies in which we are interested is approximately

$$dR/R\sim\nu dE_c/E_c\sim10dE_c/E_c, \qquad (20)$$

i.e., to determine R with accuracy $\lesssim 50\%$ it is necessary to measure the break energy with accuracy not worse than 5%.

Moreover, the condition $R\gg\lambda(E_c)$ does not yet mean that the intergalactic medium is completely opaque for γ rays with $E_\gamma\gg E_c$. When γ rays pass through the photon gas of the background radiation, there occurs not only absorption but also the generation of new γ rays by Compton scattering of the secondary electrons and positrons by the same field photons. It is obvious that the radiation spectrum that reaches the observer will be predominantly due to the development of a relativistic electromagnetic cascade in the field of the background radiation. Figure 2 shows the expected spectrum of γ rays at distance R = 100 Mpc from a source that emits monochromatic radiation with $E_\gamma = 10^{15}$ eV. The electromagnetic cascade in a black body radiation field was simulated by the Monte Carlo method in accordance with Ref. 16. By virtue of the large optical thicknesses with respect to Compton scattering and photoproduction, the expected spectrum is characterized by a weak dependence on the initial spectrum of the radiation of the source in the region of ultrahigh energies, i.e., the γ rays reach the observer with a "standardized" spectrum. As can be seen from the figure, the region of cutoff of the spectrum is somewhat "smeared" around the value of E_c expected from the condition $\lambda(E_c)$ = 100 Mpc. This obviously leads to a deterioration in the accuracy of the determination of R. At the same time, it must be noted that the radiation spectrum of Fig. 2 was calculated without allowance for the influence of the magnetic field. In a magnetic field with characteristic inhomogeneity scale Λ greater than the Larmor radius r_L the electrons will be deflected in traversing a path of order Λ through angle $\Delta\theta\sim r_L/\Lambda$.[17] For the characteristic values $H\approx3\times10^{-9}$ G and $\Lambda\sim10^{21}$ cm in the intergalactic medium,[17] we have $\Delta\theta\approx0.1$. At the same time, since the Compton mean free path of electrons with $E_e\sim10^{14}$ eV $[\Lambda_K \sim 10^{22}(E_e/10^{14}\text{ eV})^{-1}\text{ cm}]$ is greater than Λ, it is obvious that the secondary electrons are deflected from the beam without effectively radiating, i.e., a detector with angular resolution $\Delta\theta\lesssim5°$ will detect a spectrum with a sharper "drop" than the spectrum shown in Fig. 2.

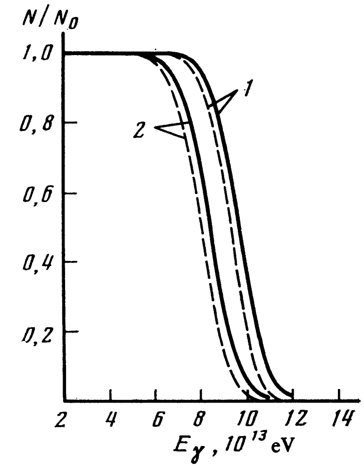

FIG. 3. Expected spectra of γ rays from a source with cosmological red shift $z_0=2.5\times10^{-2}$: 1) $y=0$, 2) $y=0.01$. The continuous curves correspond to $H_0=75$ km · sec^{-1} · Mpc^{-1}, the broken curves to $H_0=50$ km · sec^{-1} · Mpc^{-1}.

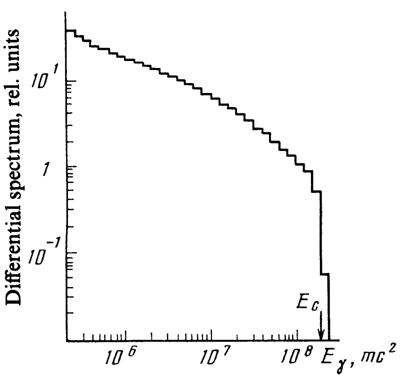

FIG. 2. Expected spectrum of γ rays calculated by the Monte Carlo method with allowance for developement of an electromagnetic cascade in the intergalactic medium. This distance to the source is R = 100 Mpc.

Whereas testing of the cosmological origin of the red shifts is a relatively simple problem, exact determination of the distances to the quasars requires high precision spectrometric measurements. If the cosmological nature of the quasar red shifts is confirmed, a possibility is opened up for determining the Hubble constant for distances $R\gg100$ Mpc: $H_0=cz_0/R$. Figure 3 shows the spectra from a source with cosmological red shift $z_0=2.5\times10^{-2}$, which corresponds to distances R = 100 Mpc for H_0 = 75 km · sec^{-1} · Mpc^{-1} and R = 150 Mpc for H_0 = km · sec^{-1} · Mpc^{-1}. As can be seen from Fig. 3, to choose between these two values of H_0 it is necessary to have an energy resolution not worse than 5%. At the same time, we must once more draw attention to the importance of sufficiently accurate knowledge of the background radiation spectrum in the submillimeter range.

To realize these aims, the best objects to investigate are the nearest quasars ($z_0\ll1$), for example 3C 273 and 0241 + 622, for which the evolutionary effects are not too important. Then observations of quasars with $z_0 \geqslant 1$ open up the possibility of studying the evolution of the background radiation in time.

3.2. Extragalactic objects with $z_0 \geqslant 1$

If the cosmological origin of the quasar red shifts is definitely confirmed, there is then a possibility of using these most distant objects in the universe to probe the background radiation in remote epochs ($z_0 \leqslant 3$). According to modern ideas, the background radiation evolves strongly. The temperature increases in proportion to $1+z$ and, accordingly, the photon density is proportional to $(1+z)^3$. In addition, the γ rays were also "hotter" at the epoch z: $E_\gamma(z) = E_{\gamma 0}(1+z)$, where $E_{\gamma 0}$ is the energy of a detected γ ray. Taken together, these factors lead to an appreciable increase in the optical thickness and, therefore, to a significant shift in the expected position of the break in the spectra of γ rays that interact with the background radiation. The position of the break will be determined from the condition $\tau(E_{\gamma_0}, z_0) = 1$, where the optical thickness τ in the case of a purely Planck distribution of the background radiation is determined by the expression (15), and z_0 is the red shift of the source. It is easy to show that for different z_0 the main dependence of the point of the break is $E_c \propto (1+z_0)^{-2}$. It is obvious that already for $z_0 \sim 0.1$ the evolutionary effects must lead to a shift of the break point by 20%.

Figure 4 shows the expected spectra of ultrahigh energy γ rays for sources with different z_0. It can be seen that if there is evolution of the background radiation in time one must expect breaks in the quasar spectra in a wide range of energies $E_\gamma \sim 10^{12}$–10^{14} eV, depending on z_0 (continuous curves). In the opposite case (no evolution of the background radiation), the positions of the breaks are near $\sim 7\times 10^{13}$ eV (dashed curve).

Thus, observations of even one quasar with $z_0 \geqslant 1$ could give information about the presence or absence of evolution of the background radiation. We note that the spectra shown in Fig. 4 were calculated for a purely Planck distribution of the background radiation and Hubble constant $H_0 = 75$ km $\cdot$ sec$^{-1}\cdot$ Mpc^{-1}. The possible deviations of the spectrum of the background radiation from the Planck spectrum, and also the uncertainty in H_0 cannot lead to a significant change in the position of the expected break; for the value of E_c depends on H_0 only logarithmically, and for the maximal possible $y = 0.055$ (Ref. 9) the energy E_c is changed by only two times (see Fig. 1). Moreover, comparison of several (at least two) objects with different z_0 makes it possible to eliminate these uncertainties and thus draw unambiguous conclusions. It is obvious that for this problem high energy resolution of the detecting apparatus is not required.

Hitherto, we have tacitly assumed that in quasars and the nuclei of active galaxies the γ ray spectrum extends to ultrahigh energies. Weighty arguments for a possible acceleration of particles and the generation of secondary (from pion decay) neutrinos and γ rays of ultrahigh energies in active galactic nuclei and quasars were given in Refs. 18 and 19. Although γ rays can be absorbed by x rays directly in the

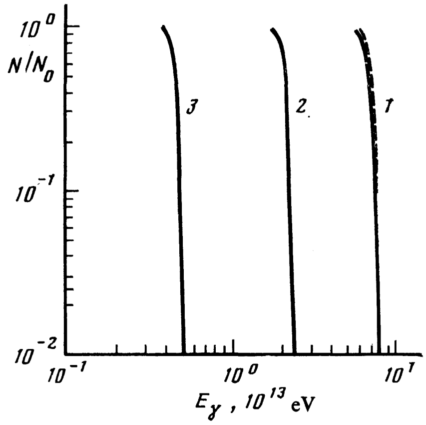

FIG. 4. Expected spectra of γ rays from source with different values of the cosmological red shift z_0: 1) $z_0 = 0.158$ (3C 273), 2) $z_0 = 1$, 3) $z_0 = 3$. The broken curve corresponds to the case when there is no evolution of the background radiation and $z_0 = 1$.

sources,[20] this is important in the first place only for γ rays of moderate energies ($E_\gamma < 10^{12}$ eV). This is because the (e^+e^-) pair production cross section decreases in accordance with the law $E_\gamma^{-1} \ln E_\gamma$ for $E_\gamma \gg m_e^2c^4/\bar{\varepsilon}$, where $\bar{\varepsilon}$ is the characteristic energy of the field photons. As a result, γ rays of ultrahigh energies ($E_\gamma \geqslant 10^{12}$ eV) overcome the "x-ray barrier" of quasars unhindered.[21] In addition, there are observational indications[22] of a possible strong anisotropy of the emission of quasars and active galactic nuclei, and this will also facilitate the escape of γ rays from the source. It is interesting to note that γ rays with $E_\gamma \geqslant 10^{12}$ eV have already been observed from the nearest active galaxy Centaurus A ($R \approx 5$ Mpc).[23]

The theoretically expected luminosities of quasars and active galactic nuclei in γ rays and neutrinos of ultrahigh energies offer hope that they may be detected in the planned experiments to detect neutrinos (the DUMAND project) and γ rays.[24] Correlated γ–ν observations are very important, since they make it possible to establish reliably the nature of the "dips" in the γ-ray spectra and simultaneously establish whether they are due to absorption by the background radiation or merely refelect features of the spectra of the accelerated protons and nuclei.

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