ed properties. In particular, a radio galaxy may behave like the well-known tube of toothpaste when squeezed too hard.

The author would like to thank Dr. L. I. Schiff for his advice and encouragement, as well as Dr. James Bardeen, Dr. Allan Moffet, Dr. Maarten Schmidt, and Dr. Peter Sturrock for helpful discussions.

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*Work supported in part by the Office of Naval Research [Nonr-220(47)] and the National Aeronautics and Space Administration [NGR-05-002-028]. This work was begun at Stanford University, where it was supported in part by the National Science Foundation and the U. S. Air Force through the U. S. Air Force Office of Scientific Research [AF 49(638)-1389].

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OPACITY OF THE UNIVERSE TO HIGH-ENERGY PHOTONS*

Robert J. Gould and Gerald Schréder
University of California, San Diego, La Jolla, California

(Received 29 December 1965)

Recently, Penzias and Wilson[1] at the Bell Telephone Laboratories have measured what appears to be extraterrestrial microwave radiation at 4080 Mc/sec at an intensity corresponding to a "brightness temperature," or equivalent temperature of black-body radiation, of 3.5 ± 1.0°K. Dicke, Peebles, Roll, and Wilkinson[2] have interpreted this radiation as the expansion–red-shifted remnant of black-body emission from a very early stage of the universe corresponding to an optically thick gas of electrons, positrons, photons, and nucleons at 10^{10} °K. During the expansion of the universe, the radiation retains its black-body character while being adiabatically "cooled" to its present value, supposed to be 3.5°K. The energy density of black-body radiation at this temperature is $\mathcal{E} \approx 1$ eV/cm^3, while the mean photon energy is $\langle\epsilon\rangle \approx 10^{-3}$ eV. The *number density* of these photons in the universe is then very large: $n \approx 10^3$ photons/cm^3. The presence of these cosmic photons has already been shown[3] to have possible observable effects due to Compton collisions with relativistic electrons associated with cosmic radio synchrotron radiation.

The purpose of the present paper is to point out another effect of the presence of these photons. This is the effect of absorption of high-energy photons traversing cosmic distances due to electron-positron pair production in photon-photon collisions. Here we give the essential results of the effect related to experiments on high-energy cosmic photons; full details will be given in a subsequent paper. The basic process involved is well known[4]; it is just the reverse of direct e^+–e^- two-photon annihilation. The pair-production process has a threshold, since in the center-of-mass system of the photons the total photon energy must be greater than the electron-positron rest energy $2m$ ($c = 1$). In fact the cross section for the process is a maximum near threshold corresponding to $\epsilon E \gtrsim m^2$, where ϵ and E are, respectively, the low- and high-energy photon energies in the lab system. Thus, for $\epsilon \sim 10^{-3}$ eV, we see that the process is most important for energies $E \gtrsim 3\times 10^{14}$ eV of the high-energy photons. Moreover, since the cross section for the process is[4] $\sigma \sim r_0{}^2 \sim 10^{-25}$ cm^2 near maximum (r_0 is the classical electron radius), the absorption mean free path for the high-energy photons can be as small as $\lambda \sim (n\sigma)^{-1} \sim 10^{22}$ cm, roughly the size of the galaxy. This is very significant, since during the past few years there have been some attempts[5,6] to detect ultrahigh-energy primary cosmic photons of energy $\gtrsim 10^{14}$ eV. In these experiments, the procedure is to look for extensive air showers (EAS) containing an abnormally low number of muons, which would indicate that the showers were initiated by an electromagnetic rather than a nuclear process. In fact both the group[6] from the Lodz Institute and the Cosmic Physics Laboratory of the Centre d'Etudes Nucléaires operating at sea level and the group[5] from the University of San Andres, MIT, and the University of Tokyo operating at high altitude (5200 m) on Mt. Chacaltaya in Bolivia have indeed reported the occurrence of muon-poor or muonless showers at a frequency about 10^{-3} of the number of ordinary showers at primary particle energies of 10^{14} eV. In addition, significantly, the data on arrival directions of the low muon showers shows essentially no anisotropy in galactic coordinates, indicating that the (assumed) photons are of extragalactic origin.

Attenuation of cosmic photons by the $\gamma+\gamma' \to e^+ + e^-$ process was first considered by Nikishov[7] for absorption by (~eV) optical stellar photons; he showed that the effect can be appreciable for high-energy photons of energy ~10^{12} eV. Nikishov's formulation can be made more general to give the absorption probability from interaction with an (undiluted) black-body photon gas at any temperature T. One can show (details given elsewhere) that the absorption probability per unit photon path length for photons of energy E is ($\hbar = c = 1$)

$$\frac{d\tau_{\text{abs}}}{dx} = \frac{\alpha^2}{\pi\Lambda}\left(\frac{kT}{m}\right)^3 f(\nu); \tag{1}$$

here τ_{abs} is the absorption optical depth, $\alpha^{-1} = 137$, $\Lambda = m^{-1}$ is the electron Compton wavelength, $\nu = m^2/EkT$, and $f(\nu)$ is a function computed essentially from an integration over angles and energies of the low-energy black-body photon spectrum. It has the asymptotic forms

$$f(\nu) \sim (\pi^{1/2}/2)\nu^{1/2}e^{-\nu}, \quad \nu \gg 1,$$

$$\sim (\pi^2/3)\nu \ln(0.117/\nu), \quad \nu \ll 1,$$

and has a maximum value ≈ 1 at $\nu \approx 1$. We give the absorption probability as a function of energy for $T = 3.5$°K in Fig. 1. It is seen that the absorption probability $d\tau_{\text{abs}}/dx$ is greater than the reciprocal of the "Hubble radius" R_H(~10^{28} cm) or "radius of the universe" for $10^{14} < E < 10^{22}$ eV. For photons in this energy range, the absorption optical depth to the edge of the universe would be greater than unity. That is, we could "see" only out to a distance $d \sim (d\tau_{\text{abs}}/dx)^{-1}$ in the universe. We see from Fig. 1 that for $E = 10^{16}$-10^{17} eV, d is only about 10^{23} cm. This has an important consequence for the experiments on muon-poor EAS. If, as it seems, the (supposed) $\approx 10^{14}$ eV photons are of extragalactic origin, they can be coming from sources at distances $\approx 10^{26}$-10^{28} cm. However, recently[8] the experimental group on Mt. Chacaltaya have been accumulating data on larger showers containing 10^7-10^8 particles corresponding to primary energies of 10^{16}-10^{17} eV. Of the 12 638 of these showers detected so far, none have been found to be muon-poor. Our prediction is that no muon-poor showers corresponding to primary energies of 10^{16}-10^{17} eV will be found. For, as is seen from Fig. 1, the photon absorption probability is high for these energies. In fact, if there does exist a primary high-energy cosmic-photon flux, we would predict that its spectrum will

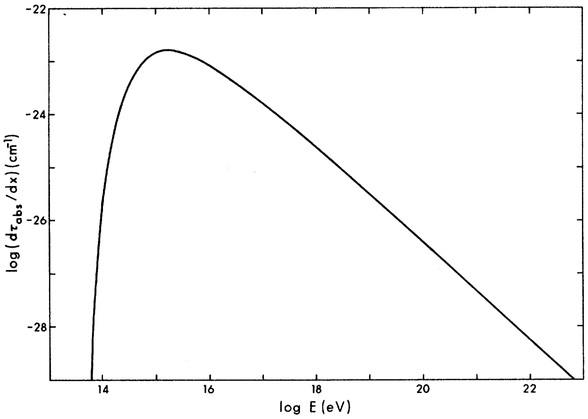

FIG. 1. Absorption probability per unit path length as a function of energy by means of the process $\gamma+\gamma' \to e^+ + e^-$ for high-energy photons traversing a black-body photon gas at 3.5°K. The absorption probability for interaction with a black-body photon gas at other temperatures may be computed with the help of this curve and Eq. (1).

show a cutoff at about 10^{14} eV due to the rapid increase in photon absorption for energies above this value. Clearly, this would provide an independent test of the black-body photon hypothesis.

Unfortunately, there is no way of distinquishing between a photon-initiated and electron-initiated shower.[9] However, due to Compton-scattering energy losses from collisions with the low-energy thermal (3.5°K) photons, the electron path length for energy loss would be only $-E(dE/dx^{-1} \approx 4\times10^{21}$ cm (about one-tenth the size of the galaxy) for $E \approx 10^{14}$ eV. Thus, under these conditions, electrons of this energy would not be likely to exist in intergalactic space unless they were produced therein by, say, π-μ-e decay following pion production in high-energy cosmic-ray nuclear collisions. But due to the large energy-loss rate for the high-energy electrons, if they are produced in this manner, there would be many more high-energy photons at the same energy in the universe due to associated π^0 decay. Still one might conceive of other means of accelerating electrons either in the galaxy or in intergalactic space. However, a cutoff in the electron spectrum observed at the earth could be expected at an energy where the path length for energy loss is roughly the size of the galaxy or galactic halo. This occurs at about 10^{13} eV–about an order of magnitude smaller than the cut-off energy expected in a cosmic photon spectrum due to the $\gamma=\gamma' \to e^+ + e^-$ process.

We have benefited from conversations with H. Bradt, J. E. Felten, P. Goldreich, and P. Morrison. We are grateful to Dr. Bradt for informing us of the recent results of his and his colleagues prior to publication.

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*Work supported in part by the National Science Foundation and in part by the National Aeronautics and Space Administration through Contract No. NsG-357.

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