EFFECT OF PHOTOMESON PRODUCTION BY THE UNIVERSAL RADIATION FIELD ON HIGH-ENERGY COSMIC RAYS

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We have made a detailed calculation of the lifetime and attentuation mean free path of high-energy cosmic rays against photomeson production. The calculation utilized the results of recent laboratory studies of photomeson production which have become available since 1966. The implications of the result are discussed.

Shortly after the discovery of the universal microwave thermal radiation field by Penzias and Wilson[1] it was noted by Greisen[2] and independently by Zatsepin and Kuz'min[3] that such radiation would have a strong attenuating effect on cosmic rays with energies exceeding 10^{11} GeV. Cosmic rays in this energy region interact with the thermal photons to produce pi mesons. These photoproduction reactions can occur because the thermal photon looks like a high-energy gamma ray in the rest system of the cosmic ray. The mesons resulting from the interaction carry off a significant fraction of the energy of the cosmic ray and may therefore attenuate the cosmic-ray spectrum above 10^{11} GeV. Indeed, both Greisen and Zatsepin and Kuz'min suggested that there may be a cutoff in the cosmic-ray spectrum in the vicinity of 10^{11} GeV. Zatsepin and Kuz'min presented a calculation of the characteristic lifetime for the cosmic rays against photomeson production. The purpose of this Letter is to present the results of a more detailed calculation of the lifetime, using the results of recent laboratory studies of photomeson production. The implications of these results will also be briefly discussed.

To determine the effect of photomeson production on the cosmic-ray spectrum, we must first define the kinematics of the photon-proton interaction. As in the discussion of Greisen and Zatsepin and Kuz'min, we consider the effect on protons interacting with the high-density universal microwave field. The temperature of this field has been determined to be 2.7°K (Stokes, Partridge, and Wilkinson)[4] yielding an average photon energy $\epsilon \simeq 6\times10^{-4}$ eV and a photon density of $n_\gamma \simeq 4\times10^2$ cm^{-3}. Denoting quantities in the proton rest system by a prime and quantities in the collision c.m. system by an asterisk and leaving quantities in the laboratory system unprimed, the Doppler relation gives

$$\epsilon' = \gamma\epsilon(1-\beta\cos\theta), \tag{1}$$

where $\gamma = E_{pi}/M_p$, E_{pi} is the initial energy of the proton, $\beta = (1-1/\gamma^2)^{1/2}$, and θ is the angle between the momentum vectors of the photon and the proton in the laboratory system. The c.m.-system quantities are determined from the relativistic invariance of the square of the total four-momentum of the photon-proton system. This invariance leads to the relation

$$s = (\epsilon^* + E_{pi}^*)^2 = M_p^2 + 2M_p\epsilon'. \tag{2}$$

Therefore, the c.m.-system Lorentz factor for the system is given by

$$\gamma_c = E_{pi} + \epsilon/\sqrt{s} \simeq E_{pi}/(M_p^2 + 2M_p\epsilon')^{1/2}. \tag{3}$$

The strongest final-state channels observed for photomeson production have been two-particle states such as

$$\begin{aligned} \gamma + p &\to N + \pi \\ &\to \Delta + \pi \\ &\to N + \rho \\ &\to N + \omega \end{aligned} \tag{4}$$

(Cambridge bubble chamber group,[5-7] Fretwell and Mullins,[8] and Buschhorn et al.[9]). If we label the particles produced in such states a and b, the c.m.-system energies of the particles are uniquely determined by conservation of energy and momentum and are given by

$$E_{a,b}^* = (s + M_{a,b}^2 - M_{b,a}^2)/2\sqrt{s}. \tag{5}$$

Therefore, the average laboratory energies of the particles are

$$\begin{aligned} \langle E_{a,b}\rangle &= \gamma_c E_{a,b}^* \\ &= \tfrac{1}{2}E_{pi}\left(1 + \frac{M_{a,b}^2 - M_{b,a}^2}{s}\right). \end{aligned} \tag{6}$$

For the important case of single-pion production, the inelasticity of the interaction in the laboratory system is found from Eq. (6) to be

$$K_p = 1 - \frac{\langle E_{pf}\rangle}{E_{pi}} = \frac{1}{2}\left(1 + \frac{M_\pi{}^2 - M_p{}^2}{s}\right), \tag{7}$$

where E_{pf} is the final energy of the proton. The threshold energy for the production of N pions is found from Eq. (2) to be

$$\epsilon_{\mathrm{th},N\pi}{}' = NM_\pi(1 + NM_\pi/2M_p) \tag{8}$$

so that $\epsilon_{\mathrm{th},\pi}{}' = 145$ MeV and the threshold inelasticity is 0.126.

The collision and attenuation mean free paths for cosmic-ray photomeson interactions are given by $\lambda_{\mathrm{coll}} = (n_\gamma\sigma)_{\mathrm{eff}}{}^{-1}$ and $\lambda_{\mathrm{attn}} = (K_p n_\gamma \sigma)_{\mathrm{eff}}{}^{-1}$. For the mean-free-path determinations, it is necessary to use effective quantities because the basic kinemetical quantity involved in interaction, the quantity s, is uniquely determined by ϵ' through Eq. (2) whereas ϵ' is not uniquely determined by ϵ, but is spread out over the energy range given by Eq. (1) for $-1 \leq \cos\theta \leq 1$. Since $\beta \simeq 1$ we may consider the energy range of ϵ' to be given by $0 < \epsilon' < 2\gamma\epsilon$. The thermal-photon density spectrum $n_\gamma(\epsilon)d\epsilon$ is of course, given by the Planck distribution,

$$n_\gamma(\epsilon)d\epsilon = \frac{\epsilon^2 d\epsilon}{\pi^2\hbar^3c^3(e^{\epsilon/kT}-1)}, \tag{9}$$

where the temperature T is taken to be 2.7°K. The lifetime of the cosmic ray against attenuation by photomeson production, $\tau(E_p)$, is equal to the attenuation mean free path divided by the cosmic-ray velocity c. It is given by the expression

$$\tau(E_p) = 2\gamma^2\hbar^3\pi^2c^2\left[\int_{(\epsilon_{\mathrm{th}}'/2\gamma)}^{\infty}\frac{d\epsilon}{\exp(\epsilon/kT)-1}\int_{\epsilon_{\mathrm{th}}'}^{2\gamma\epsilon} d\epsilon'\epsilon'\sigma(\epsilon')K_p(\epsilon')\right]^{-1}. \tag{10}$$

Recent experimental studies of photomeson production (Ref. 5-9, and Chasan, et al.[10]), have led to the determination of $\sigma(\epsilon')$ and $K_p(\epsilon')$ and these data are represented by the functions given in Fig. 1. These values were used in Eq. (10) for a numerical evaluation of the attenuation mean free path λ_{attn} and characteristic lifetime τ, respectively. The results of this calculation are shown in Fig. 2.

Figure 2 indicates that the characteristic lifetime drops sharply from 10^{12} yr at 3×10^{10} GeV to

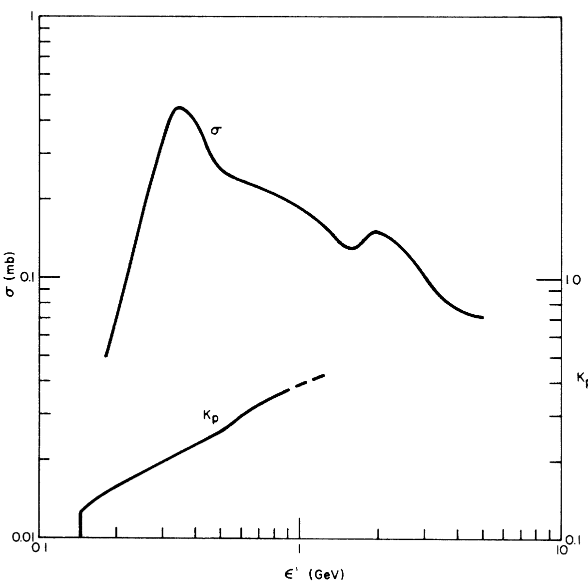

FIG. 1. Total photomeson production cross section and inelasticity as a function of gamma-ray energy in the proton rest system.

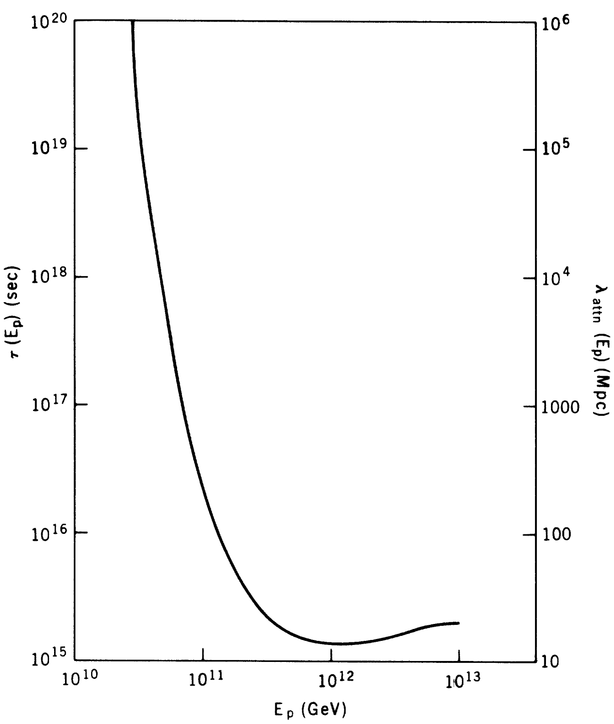

FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

10^{10} yr (the age of the universe) at 6×10^{10} GeV to slightly less than 10^9 yr at 10^{11} GeV and reaches a shallow minimum of about 5×10^7 yr near 10^{12} GeV. The sharp drop in the lifetime below 10^{11} GeV is caused by a sharp increase in the photoproduction cross section in the region of the $\Delta(1.236)$ pion-nucleon resonance, combined with a steady increase in the inelasticity, as can be seen in Fig. 1. In the region between 10^{11} and 10^{12} GeV the lifetime declines more slowly. In this region, a steady increase in inelasticity is partially offset by a decline in the cross section. Above 10^{12} GeV the photomeson cross section continues to decrease to a value of about 50 μb so that the characteristic lifetime rises slightly again to a value somewhat greater than 10^{15} sec. These new results yield lifetimes which are higher than those of Zatsepin and Kuz'min for three reasons: (1) The asymptotic cross section taken here is approximately half their value, (2) we have included the inelasticity factor K_p in our determination of an effective lifetime, and (3) the temperature taken here is 2.7°K, in accord with the more recent determinations of Stokes et al.

Greisen[2] and Zatsepin and Kuz'min[3] reached the conclusion that the cosmic-ray spectrum would steepen abruptly at an energy somewhat below 10^{11} GeV. Linsley[11] has observed an air-shower cosmic-ray event at 10^{11} GeV, indicating that there may be no cutoff at this energy. However, it should be noted that the conclusion of a cutoff is based on the assumption that the cosmic rays in this energy region are universal. The absence of a cutoff would imply travel times for these cosmic rays which are significantly less than the age of the universe but possibly not unreasonable.

It can be seen from Fig. 2 that cosmic rays of all energies may reach us from distances of the order of 10-15 Mpc essentially unattenuated by photomeson production. This is the region of the local "supercluster" of galaxies (de Vaucouleurs)[12] which includes the large Virgo cluster of galaxies, the intense Virgo A (M87) radio source, and the exploding galaxy M82. Since cosmic rays at cosmological distances are attenuated by the Hubble red shift and the local supercluster may be a relatively dense and immediate region of cosmic-ray sources, it may well be that the majority of observable extragalactic cosmic rays originate in sources within the local supercluster system.

If the average value of the intergalactic magnetic field is less than or equal to 10^{-8} G, the gyroradius of a 10^{11}-GeV cosmic ray will be greater than or equal to 10 Mpc. Therefore, the travel paths of these particles are not significantly lengthened in reaching us from sources within the local supercluster.

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