X-641-68-69
PREPRINT

PHOTOMESON-PRODUCTION BY THE UNIVERSAL MICROWAVE THERMAL RADIATION FIELD AND THE HIGH-ENERGY COSMIC RAY SPECTRUM

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March 1968

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February 1968

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ABSTRACT

A reexamination of the effect of photomeson-production by the universal microwave thermal radiation on the cosmic ray spectrum above 10^{11} GeV leads to the conclusion that the cosmic ray spectrum may not steepen abruptly above that energy as previously thought.

The production of high energy mesons resulting from the interaction of cosmic-rays with low energy photons results in two effects of astrophysical interest. As was pointed out by Hayakawa[1,2], the resultant photoproduction of neutral pions yields gamma rays having energies greater than 10^8 GeV whose flux may be more intense than the gamma-ray flux from cosmic-ray proton-proton collisions.

The other effect of the photomeson production process arises because of the energy lost by the cosmic-rays and carried off by the pions. The

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energy-loss process results in a depletion of cosmic rays having energies greater than the threshhold energy for photomeson production. With the discovery of the universal microwave field[3] this energy loss process gained added significance and its effect on the cosmic-ray spectrum above 10^{11} GeV was recognized by Greisen.[4] He concluded that the cosmic ray spectrum will steepen abruptly (and perhaps even end) above 10^{11} GeV and that Linsley's observation[5] of a cosmic ray of energy in the 10^{11} GeV region "appears surprising".

The purpose of this letter is to point out that a reexamination of the cosmic photomeson production process does not necessarily lead to Greisen's strong conclusion and may even be compatible with the opposite conclusion, that photomeson production may have a negligible effect on the cosmic-ray spectrum above 10^{11} GeV. Such a conclusion is more compatible with Linsley's observation and is of importance to experimentalists in planning detectors to study the cosmic-ray spectrum in this region.

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 Greisen's discussion, 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[6] yielding an average photon energy $\epsilon = 6 \times 10^{-4}$ eV and a photon density of $n_\gamma = 4 \times 10^2$ cm^{-3}. Denoting quantities in the proton-rest-system by a prime and quantities in the collision c.m.s. 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, $\beta = \sqrt{1 - 1/\gamma^2}$ and θ is the angle between the momentum vectors of the photon and the proton in the laboratory system. The c.m.s. 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.s. Lorentz factor for the system is given by

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

The strongest final-state-channels observed for photomeson production have been two-particle states such as[7-11]

$$\gamma + p \longrightarrow \begin{cases} N + \pi \\ \Delta + \pi \\ N + \rho \\ N + \omega \end{cases} . \tag{4}$$

If we lable the particles produced in such states a and b, the c.m.s. energies of the particles are uniquely determined by conservation of energy and momentum and are given by

$$E^*_{a,b} = \frac{s + M^2_{a,b} - M^2_{b,a}}{2\sqrt{s}} . \qquad (5)$$

Therefore, the average laboratory energies of the particles are

$$\langle E_{a,b} \rangle = \gamma_c E^*_{a,b} = \frac{E_{pi}}{2}\left(1 + \frac{M^2_{a,b} - M^2_{b,a}}{s}\right) . \qquad (6)$$

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

$$K_p = 1 - \frac{\langle E_{pf} \rangle}{E_{pi}} = \frac{1}{2}\left(1 + \frac{M^2_\pi - M^2_p}{s}\right) \qquad (7)$$

where E_{pf} is the final energy of the proton.

The threshhold energy for the production of N pions is found from equation (2) to be

$$\epsilon'_{th, N\pi} = N M_\pi \left(1 + \frac{N M_\pi}{2M_p}\right) \qquad (8)$$

so that $\epsilon'_{th,\pi} =$ 145 MeV and the threshhold inelasticity is 0.126

The collision and attenuation mean-free-paths (mfp) for cosmic-ray photomeson interactions are given by $\lambda_{coll} = (n_\gamma \sigma)^{-1}_{eff.}$ and $\lambda_{attn} = (K_p n_\gamma \sigma)^{-1}_{eff.}$ For the mfp determinations, it is necessary to use effective quantities because the basic kinemetical quantity involved in the interaction, the quantity $\underline{s}$, is uniquely determined by ϵ' through equation (2) whereas ϵ' is not uniquely determined by ϵ, but is spread out over the energy range given by equation (1) for

$-1 \leq \cos\theta \leq 1$. We may therefore neglect the small thermal spread in ϵ and since $\beta \simeq 1$ we may consider the energy range of ϵ' to be given by $0 < \epsilon' < 2\gamma\epsilon$.

Since K_p and σ are functions of s, they are also functions of ϵ' and must therefore be averaged over ϵ' to determine the effective mean-free-paths.

The collision mfp is given by

$$\lambda_{coll}(\gamma) = \frac{n_\gamma}{2\gamma^2\epsilon^2}\int_{\epsilon'_{th}}^{2\gamma\epsilon} d\epsilon'\,\epsilon'\sigma(\epsilon') \tag{10}$$

and the attenuation mfp is given by

$$\lambda_{attn}(\gamma) = \frac{n_\gamma}{2\gamma^2\epsilon^2}\int_{\epsilon'_{th}}^{2\gamma\epsilon} d\epsilon'\;\epsilon'\sigma(\epsilon')K_p(\epsilon') \tag{11}$$

where $\gamma > \frac{\epsilon'_{th}}{2\epsilon}$ which corresponds to a proton threshhold energy of 1.1×10^{11} GeV. Below this energy, there is no attenuation of the cosmic-ray spectrum due to photomeson production.

Recent experimental studies of photomeson production [7–12] have led to the determination of $\sigma(\epsilon')$ and $K_p(\epsilon')$ and these data are represented by the functions given in Figure 1.

From equation (11) we find that the attenuation mfp drops sharply in the region 1.1×10^{11} GeV $< E_p < 3 \times 10^{11}$ Gev., having a value of about 130 Mpc (1 megaparsec $= 3 \times 10^{24}$ cm.) for $E_p = 2 \times 10^{11}$ GeV and 20 Mpc at 3×10^{11} GeV. An examination of Figure 1 shows that this sharp drop is caused by a sharp increase in the photoproduction cross-section in the region of the Δ(1.236) pion-nucleon resonance, combined with a steady increase in the inalasticity. In the region 3×10^{11} GeV $< E_p < 10^{12}$ GeV the attenuation mfp declines slowly from 20 Mpc to a minimum of about 10 Mpc. 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 attenuation mfp rises slightly again to a value between 20 and 40 Mpc.

While such mean-free-paths are small compared to the cosmological radius of the universe (3000 Mpc), it should be noted 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 "surpercluster" of galaxies[13] 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 this is the case, there will be no sharp cutoff in the observed cosmic-ray spectrum unless intergalactic magnetic irregularities significantly prolong their propagation path. At present there is no evidence for such significant irregularities.

It may also be noted that if strong attenuation above the threshhold energy should occur, the result could be an <u>increase</u> in the spectrum in the 10^{11} GeV region just below threshhold due to protons entering this region from higher energies and piling up. It is implicity assumed in this dicussion that particles can be accelerated within the local supercluster region. (A Fermi-type acceleration with $dE/dt \propto E$ may be quite efficient at such energies.)

The author would like to thank Dr. Frank C. Jones of the Goddard Space Flight Center for helpful discussing of this problem.

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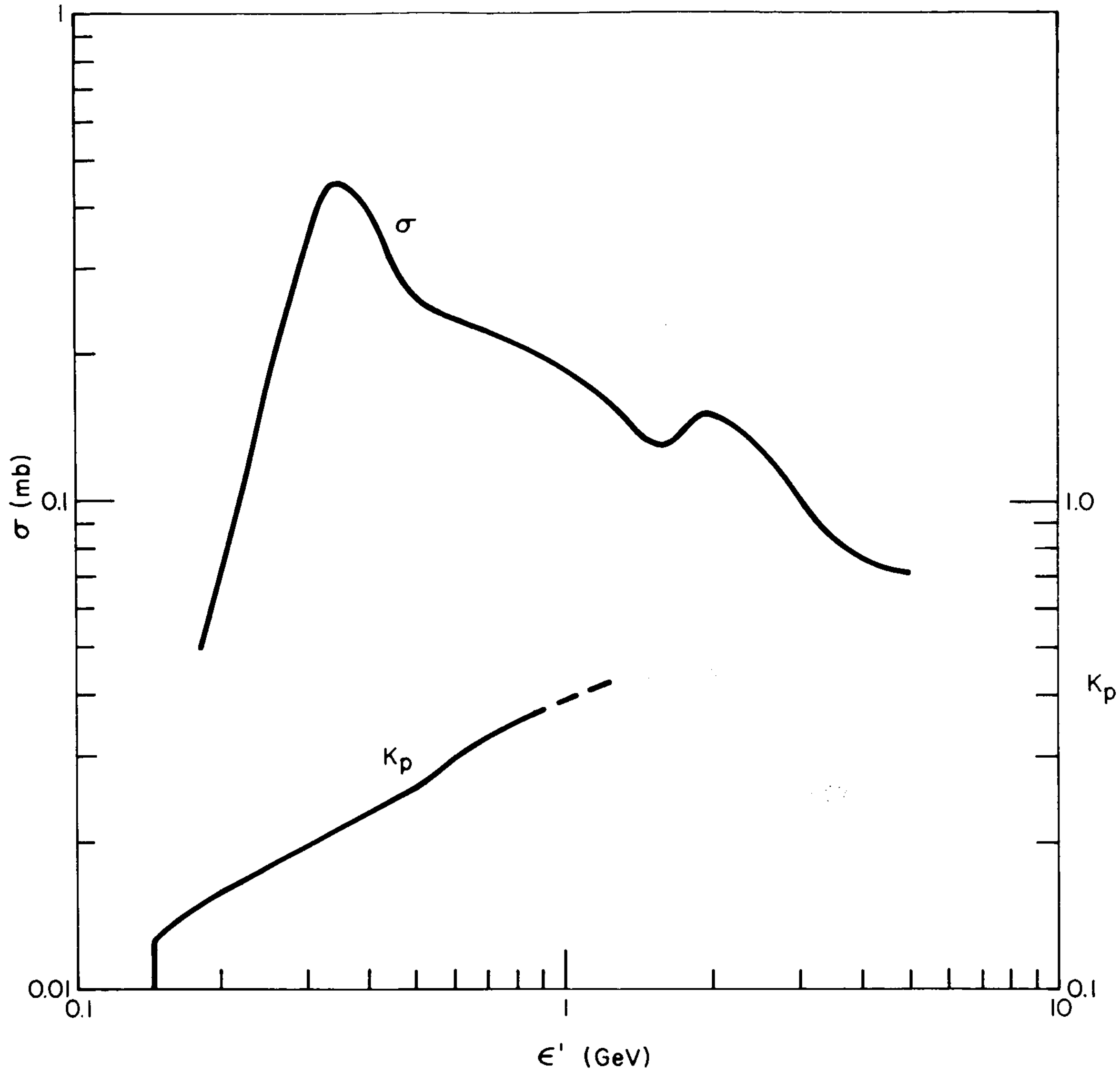

Figure 1–Total photomeson production cross-section and inelasticity as a function of gamma-ray energy in the proton-rest-system.