print No. 51, 1970 (unpublished)]. The problem of producing a high enough intensity of γ rays from this mechanism has been discussed by G. S. Bisnovaty-Kogan and R. A. Sunyaev, Astrophys. Lett. 7, 237 (1971).

[31] Note on recent experimental results: J. I. Trombka (private communication) has indicated that a recent reanalysis of the Ranger 3 results above 1 MeV is in agreement with the measurements of Vette *et al.* S. V. Golenetsky (Moscow Seminar on Cosmic-Rays and Astrophysics, 1971) has reported that new upper limits for γ rays of energies up to 3 MeV obtained by a detector aboard the low-altitude Cosmos 135 satellite are in conflict with the measurements of Vette *et al.*

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[33] Alternatively we could assume that some mechanism such as that proposed by Omnès results in the survival of some small fraction of antimatter $n_{\bar{p}} = \xi^2 n$. This assumption would yield the same Eq. (3) with a theoretical fit to the observations for $\xi^2 = 1\times 10^{-15}$.

Inclusive Reaction $\gamma + p \rightarrow \pi^- +$ Anything in the Proton Fragmentation Region*

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The inclusive reaction $\gamma + p \rightarrow \pi^- +$ anything is studied in the energy range $E_\gamma = 5.5$–15 GeV. Experimental data on the differential cross section $\partial^2\sigma/\partial P_L \partial P_T^2$ in the target fragmentation region are qualitatively similar in shape in different energy intervals, but the magnitude shows a significant decrease with E_γ in this energy range.

The term "inclusive reaction" has been used by Feynman to designate a class of reactions in which a particular type of particle (e.g., π^-) is detected in the final state, disregarding all other particles.[1] The variables which describe an inclusive reaction are P_T, x, and s, where P_T is the transverse momentum, s is the total c.m. energy squared, and $x \equiv 2P_L^*/\sqrt{s}$, where P_L^* is the c.m. longitudinal momentum. Guided by general observations on the structure of field theory, Feynman hypothesized that at sufficiently high energy, the distribution of particles in an inclusive reaction should become a function of P_T and x only. This is the *scaling* hypothesis. Yang and co-workers[2] have emphasized a related concept called *limiting fragmentation.* In this scheme, the distribution of particles of a given type is studied in the target (or projectile) rest system. This distribution $\rho(P_L, P_T)$ should approach a limit as the projectile energy increases. It can be shown that these two hypotheses are equivalent at high energies.[3]

Experimentally, the hypothesis of limiting fragmentation is approximately true for $p+p \rightarrow \pi^\pm +$ anything in the range 12–70 GeV/c,[4] for $\pi^- + p \rightarrow \pi^\pm +$ anything in the range 2.5–25 GeV/c,[5] and $K^+ + p \rightarrow \pi^- +$ anything at 12 GeV/c,[6] at least in the target fragmentation region. Thus it would be a very intriguing observation if the same were true for *photon*-induced reactions. It is well known that γp reactions have many features in common with $\pi^\pm p$ interactions. The total cross sections have a very similar energy behavior (scaled by about a factor of 200), the average transverse momentum is small ($\langle P_T\rangle \sim 0.3$ GeV/c) in both cases, and many of the same resonances are observed. These observations are approximately explained by the notion of vector dominance: The hadronlike properties of the photon apparently arise because it has the same quantum numbers as the vector mesons (ρ, φ, ω). Thus limiting fragmentation may also be a property that γp has in common with πp, pp, and perhaps other hadron-hadron collisions.

We present here results for $\gamma + p \rightarrow \pi^- +$ anything. Multiparticle final states have been studied using the Stanford Linear Accelerator Center (SLAC) 2-m streamer chamber.[7] Important features of the experiment are the 18-GeV bremsstrahlung beam, the pressurized hydrogen target, the 10.4-kG magnetic field, and 600 000 stereoscopic triads. The events studied in this analysis are the three-, five-, seven-, and nine-prong topologies (21 055, 15 304, 1918, and 184 events, respectively). These numbers of events correspond to different film samples, and appropriate weights were therefore used for each topology.

We adopt the Yang approach in examining distributions of negative tracks in the target rest system (laboratory). This approach is the most direct and simple application of our data, and it also allows easy comparison with other experiments.[8]

An experimental complication arises from the fact that the photon beam contains all energies up to 18 GeV, and therefore the energy of a given event is not exactly determinable if neutral particles are emitted. Nevertheless, we test the hypothesis of limiting fragmentation in the target-fragmentation region in the following way: We first calculate the "visible" laboratory photon energy $E_{\text{vis}} \equiv |\sum \vec{\mathrm{P}}_i|$ for each event. The index i refers to the charged tracks. Note that $E_{\text{vis}} \leq E_\gamma$, where E_γ is the *true* laboratory energy. We then choose particular energy intervals in E_{vis} and assign each event to the appropriate interval. In general, events with neutrals that carry off small amounts of energy will fall in the proper interval, while those having large amounts of energy taken by the neutrals will fall in a lower E_{vis} interval. This may introduce some distortion into the distributions of low-energy pions examined. However, it would seem unlikely that distributions which vary in shape with E_γ would be distorted in such a way as to show shapes independent of E_{vis}, because the low-energy particles studied make relatively little contribution to E_{vis}. At least on the basis of energy-balance considerations the E_{vis} assignment is relatively insensitive to the configuration of the target fragmentation particles. Thus if the data, treated in this manner, show apparent limiting in the shapes of the distributions, this can be taken as evidence for approximate actual limiting in shape.

We test for limiting in magnitude as well as shape, combining the data by means of the formula

$$\frac{\partial^2\sigma(E_{\text{vis}})}{\partial P_L \partial P_T^2} \equiv \frac{\partial^2\sigma(E_\gamma; \pm)}{\partial P_L \partial P_T^2} + \left[\frac{\sigma_{\text{tot}}(E_\gamma) - \sigma(E_\gamma; \pm)}{\sigma(E_{\text{vis}}; \pm 0)}\right] \frac{\partial^2\sigma(E_{\text{vis}}; \pm 0)}{\partial P_L \partial P_T^2}. \tag{1}$$

The first term is based on the subsample of events containing only charged particles in the final state (designated ±) and having energy E_γ that is therefore known. The second term is based on the subsample of events having at least one neutral (±0) which are therefore classified according to E_{vis}. The apparent differential cross section $\partial^2\sigma(E_{\text{vis}}; \pm 0)/\partial P_L \partial P_T^2$ is multiplied by a factor which is intended to correct for the loss of events from higher-energy intervals to lower-energy ones, due to the use of E_{vis} rather than E_γ. Values of $\sigma_{\text{tot}}(E_\gamma)$ are taken from a University of California at Santa Barbara–SLAC Collaboration,[9] whereas $\sigma(E_\gamma; \pm)$ and $\sigma(E_{\text{vis}}; \pm 0)$ are derived from the present experiment. The data, corrected in this way, are presented in Figs. 1 and 2. The accuracy of this correction is discussed below.

In Fig. 1, we compare the shapes of the P_T^2 distributions for four E_{vis} intervals ranging from 5.5 to 15 GeV. All negative tracks from all topologies are combined using a weighting based on the differing film samples used and on the event geometrical configuration.[10] Based on the number of $K^\pm$ particles present in three-constraint events, we estimate that about 95% of the negative tracks are π^-. In Fig. 1, the experimental differential cross section $\partial^2\sigma(E_{\text{vis}})/\partial P_L \partial P_T^2$ is integrated over an interval in P_L $(-0.3 < P_L < 0.3\ \text{GeV}/c)$ near zero in the laboratory system. Only representative error bars are shown. There is qualitative similarity in shape although the higher-E_{vis} points appear to decrease with P_T^2 at a somewhat faster rate.

Figure 2 shows distribution of P_L(lab) for a particular P_T interval $(0.1 < P_T < 0.2\ \text{GeV}/c)$. This restricted P_T range is near the maximum in P_T and is chosen in order that the connection between P_L and x may be approximately calculated. This distribution remains qualitatively unchanged over the E_{vis} range studied, but we note an apparent trend in that the cross sections decrease somewhat with E_{vis}.

We have used various models to understand the comparison in E_{vis} and its relationship to a comparison in E_γ. An increment in E_{vis} contains two contributions corresponding to the two terms of Eq. (1): (1) events with no neutral particles and (2) a contribution of events of higher energy E_γ where a fraction of the energy is carried off by neutral particles:

$$\frac{\partial^2\sigma(E_{\text{vis}})}{\partial P_L \partial P_T^2} = \frac{\partial^2\sigma(E_\gamma; \pm)}{\partial P_L \partial P_T^2} + \sigma(E_\gamma; \pm 0)\int_{E_{\text{vis}}}^{18\ \text{GeV}} \frac{\partial^2\sigma(E_\gamma'; \pm 0)}{\partial P_L \partial P_T^2}\, Q(E_\gamma', E_{\text{vis}}) \frac{dE_\gamma'}{E_\gamma'} \times \left[\int_{E_{\text{vis}}}^{18\ \text{GeV}} \sigma(E_\gamma'; \pm 0) Q(E_\gamma', E_{\text{vis}}) \frac{dE_\gamma'}{E_\gamma'}\right]^{-1}, \tag{2}$$

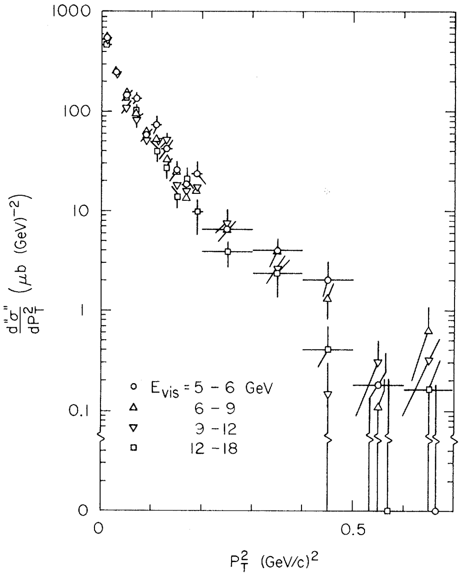

FIG. 1. Differential cross sections for the inclusive reaction $\gamma+p\to\pi^-+$anything for four intervals in E_{vis}. The error bars represent statistical errors only. We define "σ" to be the integral of $\partial^2\sigma(E_{vis})/\partial P_L\partial P_T^2$ between $P_L=-0.3$ and 0.3 GeV/c.

where $Q(E_\gamma,E_{vis})dE_{vis}$ is the probability that an event of energy E_γ has a visible energy between E_{vis} and $E_{vis}+dE_{vis}$. In this formulation, we assume that $Q(E_\gamma,E_{vis})$ does not depend on the $\vec{P}$ of the low-energy π^- under consideration, as these particles do not affect the energy balance significantly. This assumption in consistent with the approximately constant shape which we see in Figs. 1 and 2.

To obtain concrete results, we have assumed[11] various behaviors for $Q(E_\gamma,E_{vis})$ and have computed Eq. (2). We have found that an E_{vis} dependence of the amount seen in Fig. 2 is caused by an even stronger E_γ dependence. The relationship between the experimental $\partial^2\sigma(E_{vis})/\partial P_L\partial P_T^2$ as calculated from the data using Eq. (1) and the corresponding inclusive cross section $\partial^2\sigma(E_\gamma)/\partial P_L\partial P_T^2$ at a given E_γ was numerically determined from these computations. The required correction is less than 10% everywhere and is relatively independent of the form of $Q(E_\gamma, E_{vis})$.

In order to gain sufficient statistics to study the trend seen in Fig. 2, we have integrated $\partial^2\sigma(E_\gamma)/\partial P_L\partial P_T^2$ over all P_T^2 and over the range $-\infty<P_L<0.0$ GeV/c for each E_γ interval:

$$S_{-\infty}^{\;0.0}(E_\gamma)\equiv\int_{-\infty}^{0.0\text{ GeV}/c}\int_0^\infty\frac{\partial^2\sigma(E_\gamma)}{\partial P_L\partial P_T^2}\,dP_T^2\,dP_L.$$

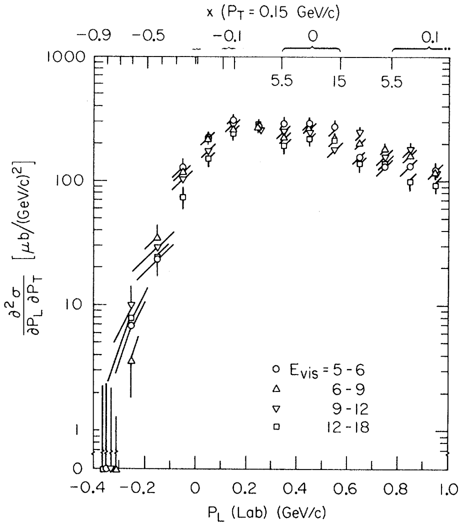

FIG. 2. The differential cross section $\partial^2\sigma(E_{vis})/\partial P_L\partial P_T$ for $0.1\leq P_T\leq 0.2$ GeV/c as a function of P_L. The error bars represent statistical errors only. The upper scale is x, evaluated for $P_T=0.15$ GeV/c and representative photon energies $E_\gamma=5.5$ and 15 GeV.

This region of backward π^- is presumably richer in proton fragmentation than the entire P_L range shown in Fig. 2.

After all corrections have been made, we find the values $S_{-\infty}^{\;0.0}(E_\gamma)=3.78\pm0.44$, 3.83 ± 0.34, 3.10 ± 0.32, and 2.47 ± 0.32 μb, for E_γ intervals centered at 5.5, 7.5, 10.5, and 15 GeV, respectively. The individual errors reflect statistics, uncertainties in the parameters of Eq. (1), and an uncertainty in the translation from E_{vis} to E_γ. In addition, we estimate an overall normalization uncertainty of ±0.3 μb, due to the simplifications inherent in Eq. (2).

At these energies, the regions of target and beam fragmentation may overlap appreciably. Thus, even the backward region considered may contain a π^- contribution from other than proton fragmentation, and an interpretation of the observed decrease of the π^- yield with E_γ may be difficult. Nevertheless, assuming that the region is dominated by proton fragmentation, it is interesting to parametrize the yields $S_{-\infty}^{\;0.0}$ in a form suggested by Regge phenomenology for target fragmentation[12]: $S_{-\infty}^{\;0.0}=A+Bs^{-1/2}$. A least-squares fit yields $A=0.1\pm1.1$ μb and $B=13.4\pm4.4$ μb GeV.[13] Thus, assuming this parametrization to be valid, it would seem that the cross section in the target-fragmentation region in the E_γ range studied is significantly above its asymptotic value.

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[12] See, for example, Chan H.-M., C. S. Hsue, C. Quigg, and J.-M. Wang, Phys. Rev. Lett. 26, 672 (1971).

[13] If we integrate over the larger range $-\infty < P_L < 0.5$ GeV/c, adopted by Chen *et al.*, Ref. 8, we find $S_{-\infty}{}^{0.5}(E_\gamma) = 52.4 \pm 2.8$, 47.5 ± 2.3, 44.4 ± 1.9, and 38.8 ± 1.6 μb for E_γ intervals centered at 5.5, 7.5, 10.5, and 15 GeV, respectively, with an overall normalization uncertainty of ± 5 μb. A least-squares fit, similar to that described in the text, yields $A = 16 \pm 6$ μb and $B = 124 \pm 26$ μb GeV when applied to these results. An overall normalization uncertainty of ± 5 μb is not included in the errors quoted.

[14] A similar study has been made at photon energies $E_\gamma = 2.8$, 4.7, and 9.3 GeV by J. Ballam, G. B. Chadwick, M. Della-Negra, R. Gearhart, K. C. Moffeit, J. J. Murray, P. Seyboth, C. K. Sinclair, I. O. Skillicorn, H. Spitzer, G. Wolf, H. H. Bingham, W. B. Fretter, W. J. Podolsky, M. S. Rabin, A. H. Rosenfeld, and R. Windmolders, contribution to the International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971 (to be published), and private communication.