Conference on High Energy Physics, Tokyo, Japan, 1978, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 743.

[2]G. L. Kane, J. Pumplin, and W. Repko, Phys. Rev. Lett. 41, 1689 (1978).

[3]The role of QCD in the production of high-p_T single photons is discussed in G. R. Farrar and S. C. Frautschi, Phys. Rev. Lett. 36, 1017 (1976); G. R. Farrar, Phys. Lett. 67B, 337 (1977); H. Fritzsch and P. Minkowski, Phys. Lett. 69B, 316 (1977); F. Halzen and D. M. Scott, Phys. Rev. Lett. 40, 1117 (1978); R. Blankenbecler, S. J. Brodsky, and J. F. Gunion, Phys. Rev. D 18, 900 (1978); R. Rückel, S. J. Brodsky, and J. F. Gunion, Phys. Rev. D 18, 2469 (1978).

[4]Substantial portions of the calculation were also checked "by hand."

[5]The Born terms A and C are $A=-2eg[\cos(\theta/2)]^{-1}$ and $C=-2eg\cos(\theta/2)$.

[6]In most experimental situations, the direction ($+z$ or $-z$) of the gluon will not be known. As a consequence, the polarization from $P(\theta)+P(\pi-\theta)$.

[7]See, for example, Rückel, Brodsky, and Gunion, Ref. 3.

[8]Recently, hard photons have been reported in an experiment at the CERN Intersecting Storage Rings. The ratio γ/π rises to about 20% at $p_T\approx 6$ GeV/c. (R. Palmer, private communication.) This effect was also seen in data reported by P. Darriulat *et al.*, Nucl. Phys. B110, 365 (1976).

[9]Other approaches to the problem of determining the three-gluon coupling include A. De Rújula, R. Petronzio, and B. Lautrup, Nucl. Phys. B146, 50 (1978); K. Koller, T. F. Walsh, and P. M. Zerwas, Phys. Lett. 82B, 263 (1979); E. Reya, Phys. Rev. Lett. 43, 8 (1979).

Direct Photon Production from π^+p Interactions at 10.5 GeV/c

A. T. Goshaw, P. W. Lucas, W. D. Walker, J. R. Elliott,[(a)]
L. E. Evans, L. R. Fortney, and W. J. Robertson
Physics Department, Duke University, Durham, North Carolina 27706

and

I. J. Kim and C. R. Sun
Physics Department, State University of New York, Albany, New York 12222
(Received 24 May 1979)

We have studied inclusive photon production from π^+p interactions at 10.5 GeV/c and found a source of centrally produced direct photons which accounts for (46 ± 9)% of all photons detected with P_L^* and P_T between 0 and 20 MeV/c. The experimental data are found to be in good agreement with a calculation of hadronic inner bremsstrahlung.

Experimental information about direct photon production from hadronic interactions is quite limited. Rather detailed measurements have been made of hadronic bremsstrahlung from elastic πp (Ref. 1) and pp (Ref. 2) collisions at low energies (beam momenta below ~1 GeV/c), but there are few data at high energies where inelastic processes are dominant. Three measurements have been reported from pp collisions at high center-of-mass energies (30 to 53 GeV) where direct photons with P_T greater than 2 GeV/c were observed.[3] Other experimental searches have either reported negative results[4] or postulated the decay of new particles as sources of observed anomalous photon signals.[5]

In this Letter we report a measurement of direct photon production from inelastic π^+p interactions with a center-of-mass energy of 4.5 GeV. Our results are relevant to studies of direct electron production since direct photons can produce e^+e^- pairs by means of internal conversion.

The experiment was done in the Stanford Linear Accelerator Center's 82-in. bubble chamber filled with a hydrogen-neon mixture having a radiation length of 125 cm. The chamber was exposed to a 10.5-GeV/c π^+ beam and the resulting interactions selectively scanned for those apparently occurring on free protons. We report here on data from a sample of 33 676 π^+ interactions of which about $\frac{2}{3}$ occur on free protons and $\frac{1}{3}$ on protons loosely bound in neon nuclei; these events consist of 10 275 inelastic two-prongs, 19 990 four-prongs and 3411 six-prongs. The photons produced from these interactions were detected with an efficiency of about 25% by means of e^+e^- pair production in the hydrogen-neon liquid.[6]

The evaluation of background sources of low-energy photons is especially important in this experiment since we are attempting to measure a direct-photon signal that occurs at low energies. The most serious potential background is that caused by the bremsstrahlung of secondary electrons and positrons (photon e^+e^- pairs, Dalitz pairs, knockon electrons, etc.). Fortunately, bremsstrahlung photons can be well associated with their parent electrons, and a combination of geometric cuts and physicsts' decisions have been used to remove this background. Spurious e^+e^- pairs produced by photons coming from random hadronic interactions in the bubble chamber, or upstream of it, have been monitored by measuring how often such converted photons point to random spots on noninteracting beam tracks. We find that the uncertainty introduced into our final photon data due to the removal of these unassociated e^+e^- pairs is small.[7]

After weighting the e^+e^- pairs to correct for all detection losses, we obtain a total of 103 000 photons.[6] Most of these (~96%) come from the decay of π^0's produced in the primary π^+p collisions. For the purpose of this study we want to remove those photons coming from the secondary electromagnetic decay of hadrons and attempt to isolate those coming from either the bremsstrahlung of produced charged hadrons [Fig. 1(a)] or other direct photon-production mechanisms [Fig. 1(b)]. We proceed by analyzing the Feynman-x distribution of the photons which is shown in Fig. 2(a). The dashed curve is the photon contribution estimated to come from the decay of mesons other than π^0's while the dotted curve shows the additional photons from baryon decays (mostly $\Sigma^0 \to \Lambda\gamma$). These were obtained from a Monte Carlo calculation using measured, or where necessary estimated, hadron-production cross sections and known photon-decay mechanisms.

After subtracting the non-π^0-decay photons from the total data sample, we then use the x distribution of the remaining photons to determine the x distribution of the π^0's. In fact, the photon data

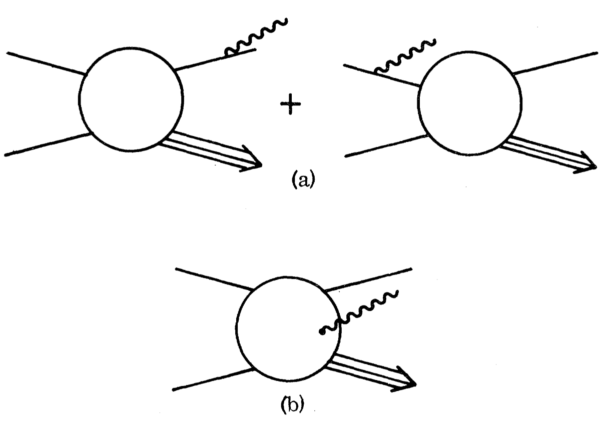

FIG. 1. Direct photon production from hadronic collisions. (a) Photon emission from external particle lines. (b) Photon emission from virtual particles.

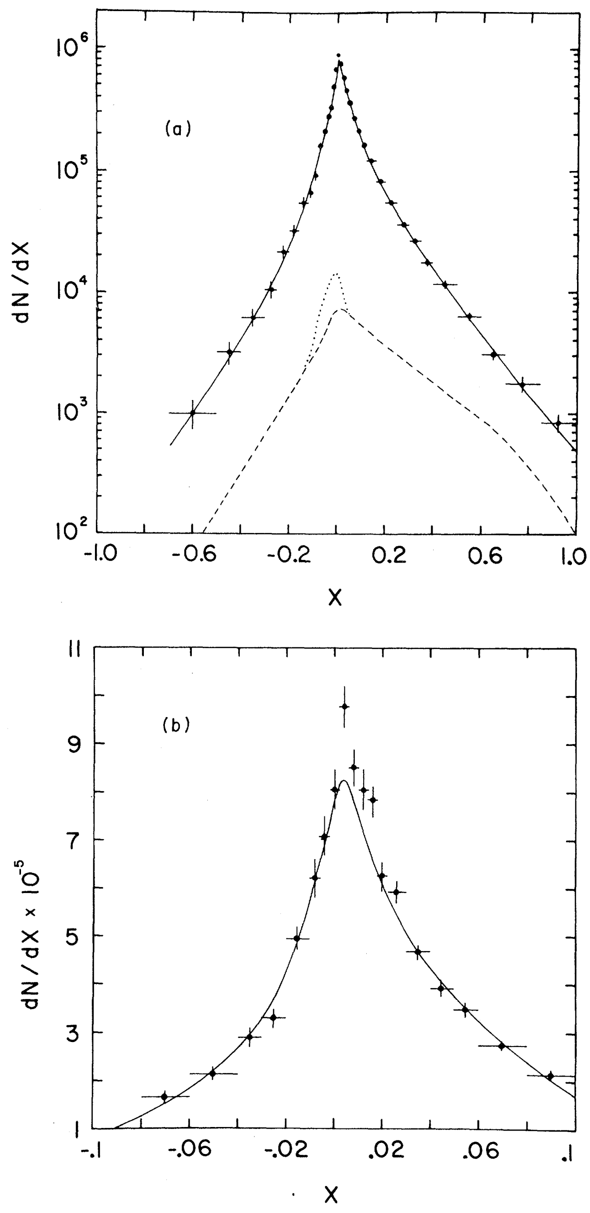

FIG. 2. (a) The Feynman-x distribution of all photons. The dashed (dotted) curve is a calculation of non-π^0-decay photons produced from the electromagnetic decay of mesons (baryons). The solid curve is our best estimate of photon production from the electromagnetic decays of all hadrons. (b) The same data as shown in (a) but on an expanded x scale.

overdetermine the x distribution of the π^0's. The simple kinematics of the decay $\pi^0 \to \gamma\gamma$ can be used to show that the photon data with $|x_\gamma| > m_{\pi^0}/2P_{max}^* = 0.031$ determine the π^0 distribution for all x values. Therefore we can predict the distribution of photons expected from π^0 decays in the region $|x_\gamma| < 0.031$ and measure any additional photon signal occurring there. To make this prediction, we took the π^- produced in the π^+p interactions as a starting point for a fit to the x distribution of the π^0's. A Monte Carlo program simulated a decay "π^-" $\to \gamma\gamma$ and the x distribution of the π^- was weighted by a smooth function of the x variable of the π^- until the simulated photon-decay spectrum fitted that which was observed for $|x_\gamma| > 0.03$. The fit obtained is excellent and, added to the calculated non-π^0-decay photons, is shown by the solid curve in Fig. 2(a). At this point in our analysis we have, therefore, determined all photon distributions for known hadron decays under the assumption that the π^- and π^0 production at the same x value has the same P_T distribution. Our final direct-photon signal is insensitive to this assumption.

Figure 2(b) shows in more detail the data for centrally produced photons. The solid curve is the expected x distribution for secondary decay photons and is in good agreement with the data except in the region $0 \leq x \lesssim 0.01$. There we observe about a 4.0-standard-deviation photon excess. The source of this excess can be further isolated by plotting the P_T^2 distribution for those photons with $0 \leq x \leq 0.01$. This is shown in Fig. 3(a) where, once again, the solid curve is the photon contribution expected from all known hadron decays. Here a large and well-isolated anomalous photon signal is seen with $P_T^2 \lesssim (20\ \mathrm{MeV}/c)^2$. For comparison, Fig. 3(b) shows the

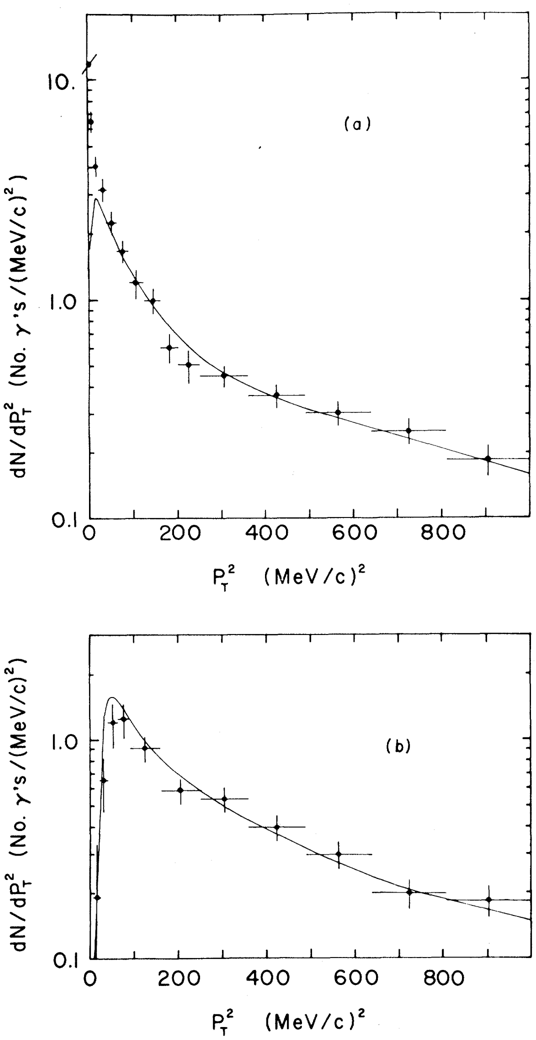

FIG. 3. The P_T^2 distribution of measured photons compared to that expected from the electromagnetic decays of hadrons. (a) Photons with $0 \leq x \leq +0.01$. (b) Photons with $-0.01 \leq x < 0$.

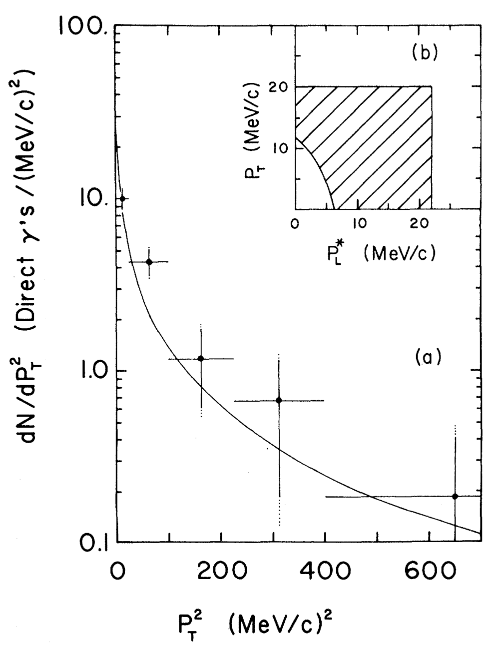

FIG. 4. (a) The P_T^2 distribution of the measured direct-photon signal. The solid vertical error bars represent statistical errors while the dotted extensions indicate the added error caused by the systematic uncertainty of the photon subtraction due to secondary hadron decays. The solid curve shows the result of a QED calculation of inner bremsstrahlung. (b) The kinematic region (shaded area) over which the direct-photon signal was measured.

P_T^2 spectrum for photons with $-0.01 \leq x \leq 0$. In this x region the entire P_T^2 spectrum agrees well with that expected from secondary hadron decays.

The excess photons observed in Fig. 3(a) are a measurement of direct photon production from π^+p interactions at 10.5 GeV/c. These are replotted in Fig. 4(a) after all decay photons have been subtracted. The exact kinematic region in which the signal was measured is shown in Fig. 4(b). Very low-energy photons are lost because an experimental cut was applied at a photon laboratory energy of 30 MeV to ensure good photon detection efficiency. There are a total of 840 $\pm$166 direct photons with $0 \leq x \leq 0.01$ ($0 \leq P_L^* \leq 22$ MeV/c) and $P_T \leq 20$ MeV/c. The error includes statistical effects and the uncertainty in all background subtractions. This direct-photon signal amounts to $(0.82 \pm 0.16)\%$ of all photon production and $(45.5 \pm 8.9)\%$ of the photons produced in the kinematic region shown in Fig. 4(b).

The most likely source of these direct photons is the inner bremsstrahlung process shown in Fig. 1(a). We have made a calculation of the photon spectrum due to this process under the assumption that the hadronic part of the matrix element, with all external particle lines on the mass shell, can be used to approximate the same matrix element with a soft photon on one external hadron line. This procedure was first suggested by Low and is equivalent to using the first term in the soft-photon expansion for the complete matrix element.[8] This term is both gauge and Lorentz invariant and contains no free parameters. The bremsstrahlung cross section in this approximation is given by

$$\frac{d\sigma^\gamma}{d^3\vec{k}}=\frac{\alpha}{(2\pi)^2}\frac{1}{\omega}\int d^3\vec{P}_1\cdots d^3\vec{P}_n\left(\sum_{i,j}\frac{-Q_iQ_jP_i\cdot P_j}{(k\cdot P_i)(k\cdot P_j)}\right)\frac{d\sigma^h}{d^3\vec{P}_1\cdots d^3\vec{P}_n},$$

where the P_i ($\vec{P}_i$) denote four- (three-) momenta of the external hadrons and the Q_i their charges.[9] k ($\vec{k}$) is the four- (three-) momentum of the bremsstrahlung photon and ω its energy. The charged-hadron–production cross section, $d\sigma^h/d^3\vec{P}_1\cdots d^3\vec{P}_n$, was derived from measurements of all charged tracks, on an event-by-event basis, of the π^+p interactions used in this analysis. This procedure includes the charged-particle correlations exactly and results in a better evaluation of the bremsstrahlung cross section than has been published previously. The result, with our experimental cuts properly included, is given by the solid curve in Fig. 4(a). There is good agreement with the measured direct-photon signal. The calculated total number of direct photons is 671 compared to our measurement of 840 ± 166.

In conclusion, we have measured for the first time a low-energy direct-photon signal from inelastic hadron collisions. The data agree well with a calculation of hadronic inner bremsstrahlung. Our experimental results lend support to calculations that have been made predicting a source of soft e^+e^- pairs from the internal conversion of the hadronic bremsstrahlung.[10]

This experiment was performed at the Stanford Linear Accelerator Center, and the research was supported in part by the U. S. Department of Energy.

[(a)]Present address: Physics Department, University of Colorado, Boulder, Colo. 80302.

[1]K. C. Leung *et al.*, Phys. Rev. D 14, 698 (1976), and references therein.

[2]B. M. K. Nefkens *et al.*, Phys. Rev. Lett. 38, 876 (1977), and references therein.

[3]Some of these measurements are in disagreement. P. Darruilat *et al.*, Nucl. Phys. B110, 365 (1976); E. Amaldi *et al.*, Phys. Lett. 77B, 240 (1978); E. Amaldi *et al.*, Phys. Lett. 84B, 360 (1979).

[4]E. W. Bier *et al.*, Phys. Rev. Lett. 37, 1114 (1976); J. H. Cobb *et al.*, Phys. Lett. 78B, 519 (1978); T. E. Kalogeropoulos *et al.*, Phys. Rev. Lett. 35, 824 (1975).

[5]P. Paulopoulos *et al.*, Phys. Lett. 72B, 415 (1978); T. E. Kalogeropoulos *et al.*, Phys. Rev. Lett. 33, 1635 (1974).

[6]The experimental procedure used to obtain the photon spectrum from the e^+e^- measurements has been described in a previous publication: J. R. Elliott *et al.*, Phys. Rev. D 17, 83 (1978).

[7]The uncertainty in this background subtraction varies with x and P_T of the photon. It contributes an estimated 10% systematic error to our direct-photon signal.

[8]F. E. Low, Phys. Rev. 110, 974 (1958); T. H. Burnett and M. Kroll, Phys. Rev. Lett. 20, 86 (1968).

[9]The summation over i and j includes the two initial-state particles and therefore runs from 1 to $n+2$ where n is the number of final-state charged particles. Q and P of the initial particles are the negative of their physical values and the metric chosen has $P\cdot P=+m^2$.

[10]R. Rückl, Phys. Lett. 64B, 39 (1976); N. S. Craigie and H. N. Thompson, Nucl. Phys. B141, 121 (1978); N. S. Craigie, Phys. Rep. 47, 1 (1978).