Anomalous Production of Direct Electrons at 10, 15, and 24 GeV/c

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We find significant direct e^+ production in hadron collisions at 10, 15, and 24 GeV/c and direct e^- production at 24 GeV/c, at $\theta_{c.m.} = 90°$ at $0.5 \leq P_T \leq 1.5$ GeV/c. The e/π ratio rises at low P_T, and in all cases exceeds the level predicted from known sources for $P_T \lesssim 1$ GeV/c.

Copious production of direct leptons in proton-proton and proton-nucleus collisions has been reported.[1-7] There is contradictory evidence[5-7] about the persistence of the effect below $P_{lab} = 70$ GeV/c. The present experiment extends the measurements for $e^{\pm}$ to the energy range 10–25 GeV for $0.5 \leq P_T \leq 1.5$ GeV/c and finds, for $P_T < 1$ GeV/c, an anomalous signal unexplained by known sources. The experiment employs an unseparated positive beam which contains approximately 100%, 85%, and 50% protons at 24, 15, and 10 GeV/c, the bulk of the remainder being pions. Positrons in the beam are suppressed by a lead absorber at the intermediate focus. Electrons and hadrons resulting from collisions in a liquid-H_2 target are detected at $\theta_{c.m.}$ near 90 . The apparatus is described in the preceding Letter[8]; preliminary discussion of the results reported here may be found elsewhere.[9]

In the P_T range measured in this experiment, there is a large flux of electrons from photon conversions (Dalitz and external). To reject most of these, we require that the direct-electron sample have (a) ≤ 1.5 times minimum ionization in the downstream dE/dx counter T_{1B}; (b) no extra track in a fiducial region in PWC_1 outside T_{1B}; and (c) no count in guard counters G_{1-4} surrounding PWC_1. We express the resulting observed signal as,

$$\left(\frac{e}{\pi^-}\right)_{obs} = \left(\frac{e}{\pi^-}\right)_S \epsilon\epsilon_L f_S(1 - G_S) + \left(\frac{e}{\pi}\right)_H + \left(\frac{e}{\pi}\right)_K \epsilon\epsilon_L(1 - G_K)$$

$$+ \sum_{M=\pi^0, \eta, \omega} \frac{M}{\pi^-} \epsilon\epsilon_L \{B_D P_D \lambda_D f_D + (1 - e^{-7t/9})B_X P_X \lambda_X f_X\}(1 - G_M). \tag{1}$$

Here the first term is the contribution from the direct signal $(e/\pi^-)_S$ that we wish to measure; the remaining terms are the backgrounds from hadron contamination, K decay, and the conversions of photons from meson decay.

The quantities ϵ, f, B, P, and t have been discussed in Ref. 8. The quantity $\epsilon_L \simeq 0.75$ corrects for Landau fluctuations; it represents the fraction of the time that a single track has ≤ 1.5 times the minimum ionizing pulse height in T_{1B}. The quantities λ_D and λ_X are pair loss factors giving the probability that the pair opening angle is so large or the energy division is so asymmetric that the second member of the pair escapes detection. The factors G_S, G_K, and G_M are the probabilities for a G counter to be struck accidentally (see below). We now discuss the backgrounds and correction factors in Eq. (1) in turn.

The hadron contamination is determined directly from the data by a study of the lead-glass re-duced pulse-height distribution (Ref. 8) E_{PB}/P. This distribution is studied for direct-electron candidates satisfying the Cherenkov, PB_1, dE/dx, and G counter requirements. A well-resolved peak is seen at $E_{PB}/P = 1$. The background under this peak is the tail of the hadron sample. This background varies from 2%–3% at low P_T to 9% at high P_T.

The background from K_{e3} decays is determined by a Monte Carlo calculation from inclusive K-production data parametrized as described in Ref. 8[10]; $(e^+/\pi^-)_K$ varies from $\sim 1.5 \times 10^{-5}$ at $P_T = 0.55$ GeV/c to 0.1×10^{-5} at $P_T = 1.3$ GeV/c.

For the photon-conversion background, the η and ω cross sections are parametrized as in Ref. 8.[10] The π^0/π^- ratio is then *adjusted* to reproduce the observed number of small-angle pairs (electrons with large dE/dx in T_{1A} and T_{1B}).[11] Since we are effectively using the observed number of

small-angle pairs to predict the expected number of large-angle pairs, and since the π^0 contribution dominates, our procedure makes the calculated background quite insensitive to many of the factors in Eq. (1), including the ratios η/π and ω/π.[12] The critical factors in Eq. (1) are the loss factors λ_D and λ_X, which are calculated by a detailed Monte Carlo simulation. The factor λ_D, typically equal to 0.04, depends mainly on the Dalitz decay matrix element[13] and the apparatus geometry. The factor λ_X, typically equal to 0.01, is sensitive to details of pair production,[14] multiple Coulomb scattering,[15] and energy loss by bremsstrahlung[14] and ionization. In the case of e^-/π^-, an additional correction [not shown in Eq. (1)] for Compton conversion has been calculated. The Monte Carlo program agrees with hand calculations and with a second independent computer calculation.

The factors $G_{S,K,M}$ account for the vetoing of electrons by extra G-counter hits from the same interaction or from an accidental time coincidence. The correct weighted average of G_M is obtained experimentally by seeing how often an observed small-angle (dE/dx) pair is accompanied by a G-counter hit; typical values are $G_M = 25\%-45\%$. We $assume$ that $G_S = G_K = G_M$. Breakdown of the assumption $G_S = G_M$ would lead to a change in the absolute e/π signal but would leave its statistical significance essentially unchanged.

The effectiveness of the dE/dx cut in T_{1B} has been monitored by studying a pair sample defined by PWC_{1-2} and T_{1A}; the pair rejection is found to be at least 300:1. The efficiency of the G counters and electronics is at least 99%.

Perhaps the most crucial check of the experimental method is the comparison of results obtained with different amounts of radiator near the target. Therefore, although the bulk of the data have been taken with the bare hydrogen target $(t \sim 0.015$ radiation lengths), we have also taken test data with aluminum radiator sheets of thickness 0.018 and 0.038 radiation lengths added.

The first result of these tests is that in all cases the π^0/π^- ratios inferred from the low-mass pair rates are found to be independent of t, a result which depends critically on many of the details of the Monte Carlo corrections. As illustrated in Ref. 8 we find that overall the low-mass pair rates are consistent with the relation $\pi^0 = \frac{1}{2}(\pi^+ + \pi^-)$, with $\pi^0/\pi^- \approx 1.3-1.4$.

The second test is whether consistent direct-electron results are also obtained. Figure 1 shows e/π radiator data for each of our four data
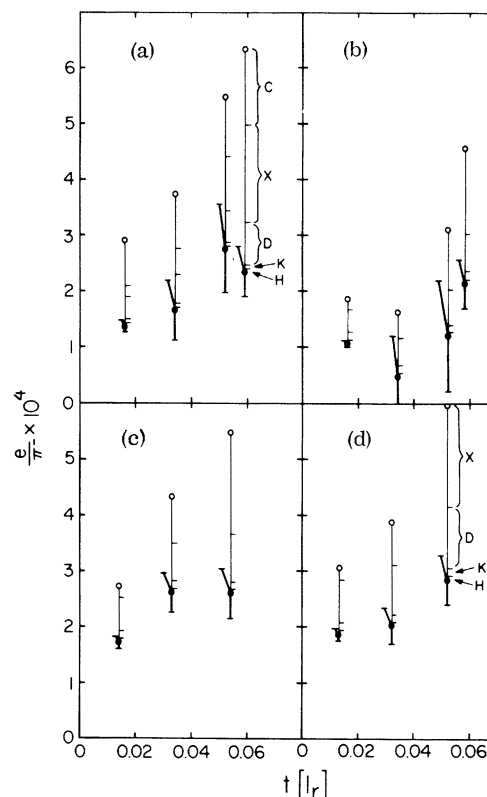

FIG. 1. Direct-electron results versus radiator thickness for (a) 24-GeV/c e^-; (b),(c),(d) 24-, 15-, 10-GeV/c e^+. The background subtraction for Compton conversions, Dalitz pairs, external pairs, hadron contamination, and K decay are shown as C, D, X, H, and K, respectively.

sets, with all data for $P_T \geq 0.5$ GeV/c combined to improve the statistical significance. The open circles give the results before background subtraction; the closed circles with error bars (statistical errors only) give the results after subtraction of the backgrounds, whose individual contributions are also shown. We note that (1) the data before background subtraction show a significant rise with t, but any reasonable extrapolation shows that there is a significant direct-electron signal[16]; and (2) the rise is almost entirely accounted for by the calculated backgrounds.

Our results for e/π^- as a function of P_T are shown in Fig. 2. The open circles give this ratio before background subtraction and the closed circles give the direct signal after background subtraction. A significant signal is seen at all energies, and all show an increase toward small P_T. Note that the direct signal is $\geq 60\%$ of the total for e^+; e^- suffers from the additional background from Compton scattering. Also shown in Fig. 2
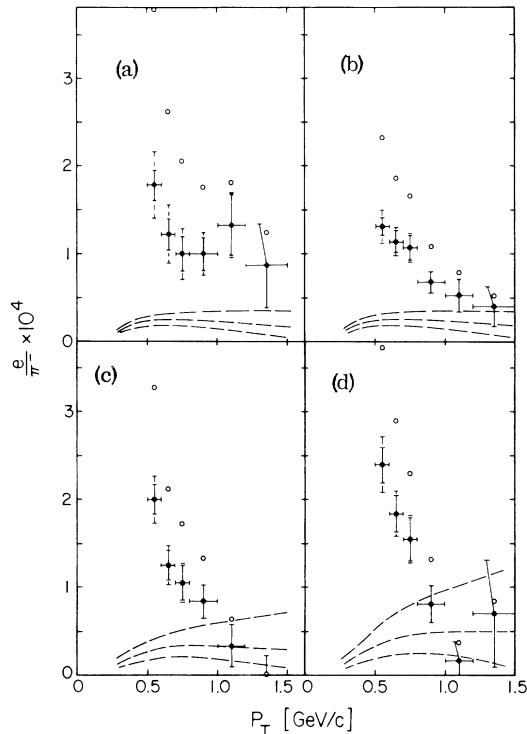
FIG. 2. Direct-electron rates versus P_T for (a) 24 GeV/c e^-; (b), (c), (d) 24-, 15-, and 10-GeV/c e^+. The values before background subtraction are also shown (open circles). The solid error bars give the statistical error in the background subtracted signal; the dashed extensions give the additional contribution from estimated systematic errors (Ref. 16) added in quadrature. The dashed curves give estimates of the minimum, most probable, and maximum likely contributions from vector-meson decay.

are the expected levels of prompt electrons from ρ, ω, and φ decays into e^+e^-.[10,17] The range of these predications represents the uncertainties in the production of the vector mesons (these contributions have not been subtracted from the data). We observe that for $P_T \geq 1$ GeV/c, our results may be consistent with the expectation based on vector-meson decays. For $P_T \lesssim 1$ GeV/c there is an anomalous residual signal. In this low-P_T range the ratio e/π at fixed P_T rises with decreasing s.

Possible sources of anomalous signal including decays of μ, Λ, Σ, J/ψ, and positrons arising from e^+ in the beam have been calculated and found to be negligible.

We make the following remarks about the anomalous signal at low P_T: (1) At 24 GeV/c, the ratio of e^- to e^+ production is $\approx 1.3 \pm 0.3$ (where the error is dominated by our uncertainty in the Compton background), and thus consistent with

an electromagnetic origin of the anomaly. (2) At 15 GeV/c, the beam Cherenkov counter partially distinguished incident π^+ and p. From the observed e^+ yields with and without a Cherenkov count, we infer that the ratio of the number of direct electrons for incident π^+ to that for incident p is 1.0 ± 0.3. (3) The rise of the prompt electron signal down to $P_T = 0.5$ GeV/c sets an upper limit on the mass of the presumed parent of the observed electrons. For two-body decays of the parent, the parent mass is required to be less than m_ρ (see the electron yields from ρ, ω, and φ decay indicated in Fig. 2). (4) The kinematic range explored by this experiment does not overlap previous work that reports observation of direct leptons,[2-5] nor does it overlap searches where no signal was found.[6,7] We note, however, that the increase in the direct-lepton signal toward low $p_\perp$ has been observed at higher energy as well,[4] and that observation of direct muons at 28 GeV/c indicate that the signal increases as one approaches $\theta_{c.m.} = 90°$ from more forward production angles.[5] (5) If the origin of the observed electrons is the production and weak decay of new particles, then σB is at least two orders of magnitude greater than most estimates of charmed-particle production at these energies.

In summary, we conclude that direct electrons are produced in π^+p and pp collisions between 10 and 24 GeV/c near $\theta_{c.m.} = 90°$. For $0.5 \leq P_T \leq 1.0$ GeV/c this production is unexpectedly large and cannot be explained by conventional decays of μ, π, K, η, ρ, ω, φ, Λ, Σ, and J/ψ. If the origin of this effect is electromagnetic, then the pair mass must be roughly in the 100–750-MeV/c^2 range.

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[9]Portions of our results have been discussed by B. G. Pope, in Proceedings of the European Physical Society International Conference on High Energy Physics, Palermo, Italy, 1975 (unpublished); and by Lederman, Ref. 1. The present Letter extends these preliminary results to lower P_T and to e^- production and includes various refinements in the calculation of expected backgrounds and analysis of the observed signal. The most important improvements were made in the radiative

corrections to electron spectra (which resulted in a reduction of the high P_T signal) and in treatment of η-decay backgrounds.

[10]Production rate estimates at 10 and 15 GeV/c include allowances for s dependence and for the beam pion content.

[11]The fitted π^0/π^- ratios are consistent with $\pi^0 = (\pi^+ + \pi^-)/2$. We neglect direct photons.

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[16]Because of the nonlinearity in t of the external conversion background, it is difficult to define an accurate extrapolation technique. Therefore, we obtain our results from the data with the bare target, using the calculated background subtractions. We have assigned systematic uncertainties of 50% and 20% to the external and Dalitz conversion background, and 30% to the Compton background.

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Experimental Tests of Pomeron Factorization in Single-Particle-Inclusive Hadron Scattering*

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Measurements of the dependence on $s = (p_a + p_b)^2$ of the cross sections for single charged hadron production in the reactions $a + b \to c + \text{anything}$ over the range 4 GeV/c $\leq p_a^{\text{lab}} \leq 250$ GeV/c are presented. Particle c is detected in a fixed interval of laboratory momentum and angle in the fragmentation region of the target proton. For the energy range studied there are significant departures from $A + Bs^{-1/2}$ energy dependence. Fits to the s dependence of the cross sections are extrapolated to $s^{-1/2} = 0$ to make seven independent tests of Pomeron factorization.

We report measurements of the cross sections for the single-particle inclusive hadron reactions $a + b \to c + \text{anything}$ where $a = \pi^+, K^+, p^+$, $b = p$, and $c = \pi^+, K^+, p^+$. The measurements were made in a small, fixed region of the phase space of particle c corresponding approximately to $P_\perp = 0.3$ GeV/c and $y_L = 0.6$, 0.4, and 0.2 for produced π, K, and p, respectively.[1] The incident momenta were 4, 6, 8, 10, 12, 15, 20, 24, 150, and 250 GeV/c. The data are interpreted using the Mueller-Regge phenomenology,[2,3] which suggests that the differential cross sections at high energy should de-

pend on $s = (p_a + p_b)^2$ according to $A + Bs^{-1/2}$. Fits to the s dependence of the measured cross sections are extrapolated to $s^{-1/2} = 0$ and the ratios of the resulting "asymptotic" cross sections are compared with the appropriate total cross-section ratios to test the prediction of Pomeron factorization:

$$\frac{E \, d^3\sigma/d^3p(ab \to c)}{E \, d^3\sigma/d^3p(a'b \to c)} \underset{s \to \infty}{=} \frac{\sigma_{\text{tot}}(ab)}{\sigma_{\text{tot}}(a'b)}, \tag{1}$$

where $\sigma_{\text{tot}}(ab)$ is the total cross section for parti-