Production of Prompt Muons in the Forward Direction by 400-GeV Proton Interactions

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The ratio of prompt negative muons to negative pions produced in the forward direction by the interaction of 400-GeV protons on copper has been determined to be 5.8×10^{-5} for 55-GeV muons, 3.05×10^{-5} for 102-GeV muons, and 1.93×10^{-5} for 230-GeV muons. The ratio of prompt positive muons to negative muons was about 1.

Recent measurements[1-3] have established that the interaction of high-energy protons with nuclei produces a large flux of prompt leptons at large transverse momenta and small values of the Feynman variable x. The ratio of prompt leptons to pions was near 10^{-4} over a large range of transverse momenta and, for different proton energies, the production of electrons and muons seemed to be about equal and the charge ratios did not differ significantly from 1. Analyses of previous measurements[4] demonstrated that prompt muon production by lower-energy protons (28 GeV) in the forward direction at high values of x was also large and the muon charge ratio was also nearly 1, though at such large values of x positive mesons are produced much more often than negative mesons. Now large transverse momentum measurements[5] at the lower proton energies (10, 15, and 24 GeV) indicate that prompt electrons are also produced at small values of x at these energies.

Since it has not been possible to account for such large fluxes of prompt muons by conventional mechanisms, it is important to study the detailed production systematics of these particles. Since there have been few measurements at small transverse momenta, we proceeded to measure the prompt muon fluxes in the forward direction, at different values of longitudinal momenta, using an incident 400-GeV proton beam at the Fermi National Accelerator Laboratory (FNAL).

The techniques used were similar to those used previously[4] for measurements at lower energies at Brookhaven National Laboratory, but

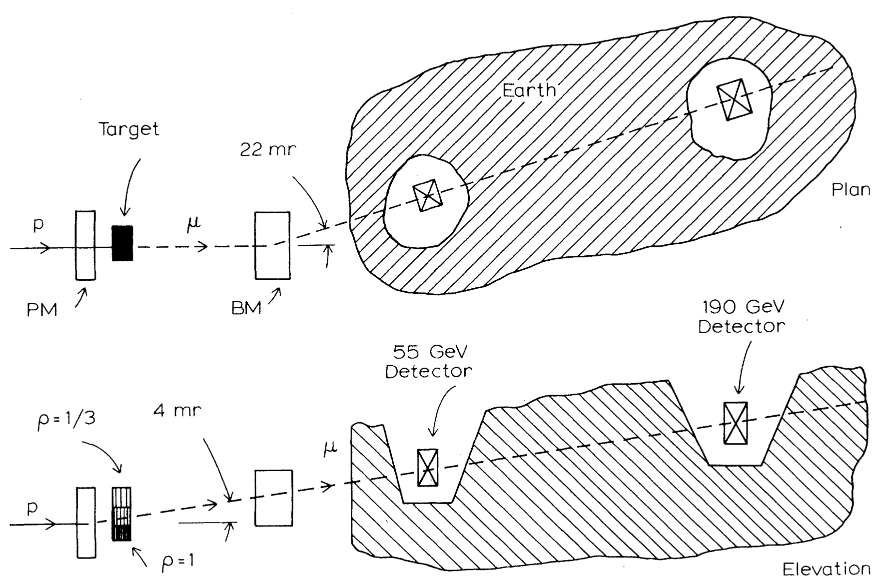

FIG. 1. Schematic representations of the configuration of the experimental apparatus (not to scale).

changed in scale to accommodate the order of magnitude increase in energies at FNAL. The diagrams of Fig. 1 present a schematic description of the experimental setup. The external proton beam passes through a pitching magnet which directs the proton beam upwards at an angle of about 4 mrad onto a variable-density target. The lowest section of the target consists of a 1-m-long section of copper; the middle section consists of a 2-m-long section of 1-in.-thick copper sections separated by 1 in. of free space; the third section is made of 1-in. copper sections separated by 2 in. of air throughout a length of 3 m. The lower two sections are backed by aluminum to a total length of 3 m. The target is mounted so that it can be raised and lowered so as to present an effective density of $\frac{1}{3}$, $\frac{1}{2}$, or 1, in units of the density of copper, to the incident proton beam. Since the flux of muons from meson decay will vary inversely with target density, the results of an extrapolation of the observed intensity with respect to the inverse density to zero inverse density (or to infinite density) gives the intensity of "prompt" muons.

The muon beam produced by the proton interactions in the target passes through about 5 m of steel shielding and through a steel-filled bending magnet 6 m long which deflects the muon beam 22 or 30 mrad, to the front or back pit detectors. Leaving the hall, the muons pass through 58 m of earth to an area located in a pit dug in the earth where detectors are situated. Leaving this region, muons pass through another 230 m of earth to detectors in a second pit. The mean minimum initial energy required of a muon to reach the back pit is about 190 GeV; muons with an initial energy greater than 54 GeV will reach the front pit.

Measurements of the muon intensity as a function of target density were made in three ways: With 400-GeV protons incident on the target, we measured the intensity of muons passing through counters set in the back pit where the effective minimum energy is about 190 GeV and the mean energy is about 230 GeV; we next measured the flux passing through the front-pit detectors where the average muon energy was about 102 GeV; and then we measured the 55-GeV flux stopping in a 2-m-thick section of ferrous concrete situated in the front pit. The results of these measurements, changed from the raw measurements only by a small correction for muons produced in material known to be upstream of the target, are shown in Fig. 2. The intercepts represent the

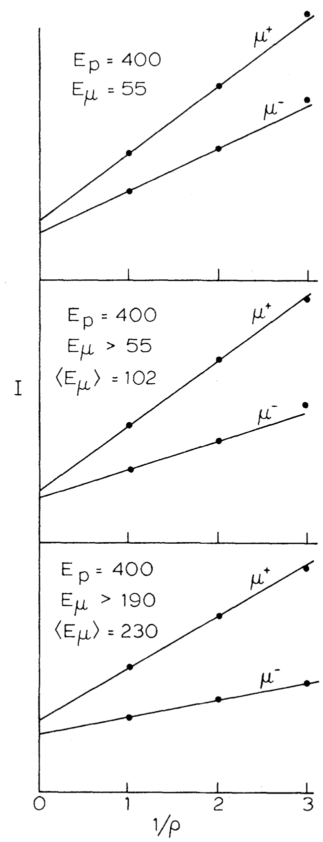

FIG. 2. Muon intensity in arbitrary units as a function of target density for various experimental conditions. The statistical errors in individual points are less than 3%.

prompt muon contribution while the slope is proportional to the intensity from the meson decays.

It is customary to discuss the prompt muon intensity in terms of the ratio of prompt muons to pions produced at the same energy and angle. In the type of experiment reported here, the quantity which is measured directly is the ratio of the prompt muons to the intensity of muons from mesons which are produced and decay in the target. At a given muon energy, the intensity of these muons from meson decay is proportional to the attenuation length of the mesons in the target material and to an integral of the meson intensity over energies greater than the muon energy. This integral then depends upon our knowledge of the variation of the meson production intensity with transverse momentum p_t and energy x_π. Since the mean momentum transfer from multiple scattering in the target assembly of about 650 MeV/c is appreciably larger than the mean transverse momentum of the muons upon production, which is about (400 MeV/c)x_μ/x_π, the detector counts a muon intensity proportional to the pion intensity integrated over (almost) the whole solid angle for production. The effective variation of the pion intensity is then proportional to dI/dx and not to $d^2I/d\Omega dx$. We can adequately express our knowledge of this pion intensity in the forward direction as

$$dI/dx = (C/x)\exp(-ax),$$

where x is the Feynman variable, used here in the laboratory system; a is taken as 6.5 for π^+ and K^+ and 8.9 for π^- and 10.0 for K^-. The parameter C was taken to be the same for positive and negative pions and $\frac{1}{7}$ as large for K mesons. Such expressions fit meson production in proton-proton interactions at high energies rather well[6,7] for values of x which are not too small, and should fit proton-nucleus interactions in the forward direction. Using these expressions, we derive the values presented in Table I for the prompt-muon to pion ratios, the mean muon energies, and the charge ratios for the muons derived from meson decay.

Corrections to the prompt muon flux to account for muon pairs produced by γ rays from neutral pion decay were made quite precisely assuming that the neutral pion flux was just $\frac{1}{2}$ of the charged pion flux. The correction was about 10% for the highest-energy muons but as large as 25% for the lowest-energy point. Even as the muon pair flux is smaller than the flux of muons from pion decays, and is derived from the same description of the pion flux, the uncertainty in the pair correction is rather smaller than the basic uncertainty in the flux of muons from pions which follows from the limitations of our knowledge of the exact form of Eq. (1).

The most serious source of systematic error in measurements of this type follows from the effects of proton-beam interactions with material upstream of the target. Such interactions of the proton-beam halo scraping on faces of guidance magnets or beam pipes can create mesons which have long decay paths and then large probabilities of decaying to muons. These muon fluxes are nearly independent of the target density and simulate prompt muon flux. Most of the contribution of such flux is eliminated by the action of the pitching magnet which is introduced into the experimental design primarily as a muon spoiler. Negative muons, in particular, are effectively swept out by this magnet. The strongest evidence that muons do not contribute much to the nominal prompt muon flux is found in an examination of the muon-charge ratios. For example, in the case of the production of muons at energies greater than 190 GeV, the ratio of positive to negative muons produced by the interaction of protons with nuclei is measured to be 3.4 for 400-GeV protons while the charge ratio for the prompt muon flux is nearly 1. For muons produced upstream of the pitching magnet there is a further differential discrimination of the negative muons. Measurements made with a material inserted in the beam upstream of this magnet showed that such muons would contribute to the nominal prompt flux but that the positive-to-negative ratio for these muons was about 15. While direct measurements with inserted material were not made in the course of the lower-energy determination,[5] the pitching magnet should be more effective in sweeping out lower-energy muons. A variety of measurements made in an effort to increase the the scraping artifically by purposeful misalignments of the beam produced no substantial effect

TABLE I. The more important experimental results: E_μ is the effective muon energy and x is the ratio of the muon longitudinal momentum to the incident-proton momentum. The ratio $(\mu^+/\mu^-)_\pi$ is the measured ratio of positive to negative muons from meson decay; the ratio $(\mu^+/\mu^-)_c$ is the ratio calculated from the relation of Eq. (1). The ratio $(\mu^+/\mu^-)_p$ is the measured charge ratio of the prompt muons while $(\mu^+/\pi^+)_p$ and $(\mu^-/\pi^-)_p$ are the ratios of the prompt muons to the pion flux from the measurements analyzed using pion intensities calculated from Eq. (1).

E_μ (GeV)	x	$(\mu^+/\mu^-)_\pi$	$(\mu^+/\mu^-)_c$	$(\mu^+/\mu^-)_p$	$(\mu^+/\pi^+)_p$ ($\times 10^5$)	$(\mu^-/\pi^-)_p$ ($\times 10^5$)
230 ± 15	0.57	3.42 ± 0.51	4.65	1.18 ± 0.10	0.903 ± 0.13	1.93 ± 0.31
102 ± 7	0.26	2.27 ± 0.35	2.08	1.15 ± 0.11	1.95 ± 0.23	3.05 ± 0.61
55 ± 3	0.135	1.66 ± 0.25	1.55	1.20 ± 0.13	5.10 ± 0.88	5.77 ± 1.01

on the nominal prompt fluxes.

While we are then confident that there is no important contribution to the prompt negative muon flux from muons produced upstream of the target, the small excess of prompt positive muons may result from such backgrounds. While the positive-to-negative ratios, measured to be of the order of 1.20 at the various energies, appear to differ from 1 by more than our estimate of systematic errors would indicate, we do not feel that we have firmly excluded the possibility that the charge asymmetric backgrounds, which we have noted, account for the observed charge differences in the prompt-muon intensities.

Although the ratios determined in these measurements are smaller than the canonical number of 10^{-4} seen at small x and at large transverse momenta, the prompt fluxes—especially at the larger values of x—are still appreciably larger, by about a factor of 5, than we can account for from conventional processes such as vector-meson decay. We note again[4] that the variation of the muon-to-pion ratios with x is similar to that which might be expected if the muon were produced by the decay of a parent state (which could be a virtual photon) which is produced with an inclusive spectrum similar to the pion spectrum.

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Photoproduction of the $\psi(3100)$ Meson at 11 GeV*

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The photoproduction of the $\psi(3100)$ meson from a beryllium target has been measured using an 11.8-GeV bremsstrahlung beam. The energy and angular dependence of the measured spectra may be obtained from an elastic nucleon cross section of the form $d\sigma/dt = (1.01 \pm 0.20) \exp[(1.25 \pm 0.20)t]$ nb/GeV^2. This cross section is exceedingly small in comparison with those of the other vector mesons.

The recently discovered $\psi(3100)$ resonance[1] is believed to be a vector meson. Our picture of the coupling of the other vector mesons to hadronic matter has been strongly influenced by the photoproduction cross sections of these particles. In particular, the cross sections at small momentum transfer are characterized approximately by an energy-independent exponential in the square of the momentum transfer. This simple empirical property has been interpreted as evidence for a diffractivelike production mechanism. Explicit models, such as vector dominance, enable one to calculate the meson-hadron couplings from these cross sections. As a consequence, it is natural to study the photoproduction of the $\psi(3100)$ in order to compare it to the other vector mesons. In this paper we report a measurement of this cross section for incident photons of energy between 9.0 and 11.8 GeV.

In this experiment a collimated photon beam of 11.8-GeV endpoint energy passes through a 2.9-g/cm^2 beryllium target, between a set of particle counters, and stops in a secondary-emission quantameter. Energetic photons and electrons leaving the target are detected in a pair of lead-glass Cherenkov hodoscopes. Each hodoscope consists of an 8×10 array of SF-2 glass elements, each 4.5 cm $\times$ 4.5 cm $\times$ 50 cm long, viewed on end by an XP1010 phototube. These hodoscopes have an energy resolution of $\delta E/E = (0.16\ \mathrm{GeV}^{1/2})/\sqrt{E}$, rms, and a position resolution of $\delta s = 0.6$ cm, rms, at 5 GeV. They were placed symmetrically above and below the beam 152.4 cm downstream of the target with their centers