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Measurement of Prompt-Muon Production in Nucleon-Nucleus Collisions*

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(Received 7 April 1975)

We have measured the production cross section for prompt muons relative to pions, produced in nucleon-nucleus interactions at incident energies from 30 to 300 GeV and for muon transverse momenta from 1 to 2.3 GeV/c. Upper limits on the production and leptonic decay of heavy particles are presented.

Several experiments have recently reported evidence for prompt-lepton production in nucleon-nucleus collisions.[1-5] Since the cross section appears to be substantially larger than estimates based on known mechanisms, it is particularly important to map out the features of this new phenomenon.

We report here a measurement of prompt-muon production in nucleon-carbon collisions over the range of incident proton energies from 30 to 300 GeV and for muon transverse momenta from 1.0 to 2.3 GeV/c.[6] The experiment was performed at the Fermilab. A detailed description of the apparatus has already been given.[7] Briefly, the detector consisted of a magnetic spectrometer equipped with eight proportional chamber planes and located at 91 mrad with respect to the accelerator's internal beam. A 21-absorption-length hadron shield was positioned between the production target and spectrometer. The first element of the absorber was a 38-cm-long Heavimet (tungsten) block beginning 5.1 cm downstream from the target. This block was located 2.1 cm below the proton beam. The rest of the absorber consisted of iron blocks located 3.5 cm below the beam. The first few elements of this shield could be withdrawn remotely to permit a measurement of the muon rate in the spectrometer as a function of the distance available for hadron decay between the target and shield. This distance was varied hourly during the experiment, as was the field polarity of the magnet. A single setting of the spectrometer's magnetic field allowed a measurement of muon momenta above 9 GeV/c for both charges simultaneously. A pair of lead-glass Cherenkov counters at the downstream end of the apparatus was used to verify that hadron contamination of the data was less than 2%, as expected behind the thick shield.

Figure 1 shows the observed muon momentum spectrum for a sample of the data taken with the longest decay path used in the experiment, 110 cm. The shape is fully consistent with that expected for muons from pion and kaon decay. The predicted spectrum was calculated from measured production cross sections[8] combined with

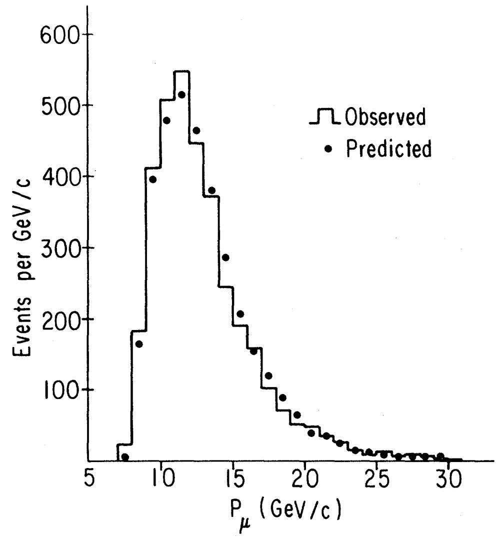

FIG. 1. Observed muon momentum spectrum, corrected for energy loss in the hadron shield.

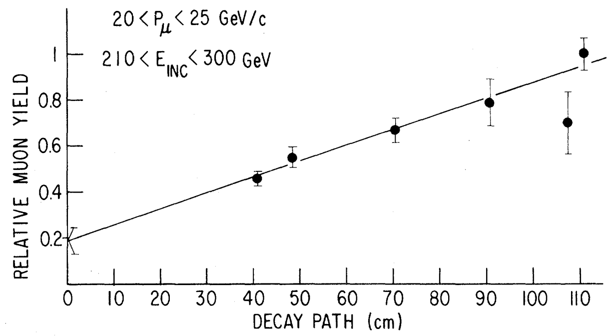

FIG. 2. Variation of muon event rate with distance between the target and the hadron absorber.

the meson-decay kinematics and folded over the detector's acceptance by Monte Carlo techniques as described below.

The muon rate was measured as a function of decay path and an extrapolation performed to zero decay path to search for short-lifetime sources. Figure 2 shows the dependence of the muon rate on the decay path for one subsample of the data. Since the slope of the extrapolation curve corresponds to the number of hadron-decay muons per unit decay path, and the intercept corresponds to the number of prompt muons, the ratio of slope to intercept, suitably combined with the hadron-decay probability, gives the ratio of the prompt-muon cross section to hadron-production cross section independently of a detailed knowledge of the detection efficiency. Only the *variation* in detection efficiency with decay path must be evaluated, not the absolute detection efficiency.

The muon rates at each decay path length shown in Fig. 2 have been corrected to the common detection efficiency of the longest decay path. For the transverse momentum intervals reported below, this relative correction is less than 12% in all but the lowest momentum interval, where it reaches 60%.

The relative corrections described above have been evaluated by Monte Carlo technique. The calculation includes energy-loss and multiple-scattering correlations, the detailed geometry of the apparatus, and the momentum resolution of the spectrometer. The correctness of the result is supported by the agreement between observed and predicted momentum spectra of Fig. 1 and by the linearity of the extrapolation in Fig. 2. Other experimental distributions have also been compared with prediction and the agreement is excellent.

These same calculations can be used to estimate the production angular distribution for the accepted events. In the case of the thickest hadron shield the accepted events have a mean production angle of 80 mrad with an rms width of 11 mrad. Less than 1% of the accepted events arise from production angles below 55 mrad. These figures include the effects of non-Gaussian multiple scattering, although the results are insensitive to its inclusion.

We emphasize that the measurement of the muon-to-hadron *ratio*, as described above, is self-normalizing. It is insensitive to electronic dead-time losses, proportional-chamber inefficiencies, and reconstruction losses. Nevertheless, the scintillator counting rates never exceeded 5 MHz, and the proportional-chamber efficiencies were typically 95% in each of the eight planes. We have searched for a possible dependence of the detector performance on the decay path and have found none.

Extrapolation plots similar to Fig. 2 have been made for a series of muon transverse momenta and incident proton energies. All show a positive intercept at zero decay path. We have investigated mechanisms which could artificially produce such an effect. The absorption lengths for pions and kaons entering the shield must be included in the effective decay path, but have been measured in the momentum range of this experiment.[9] Target-out effects were regularly monitored and are negligible. Muon production from

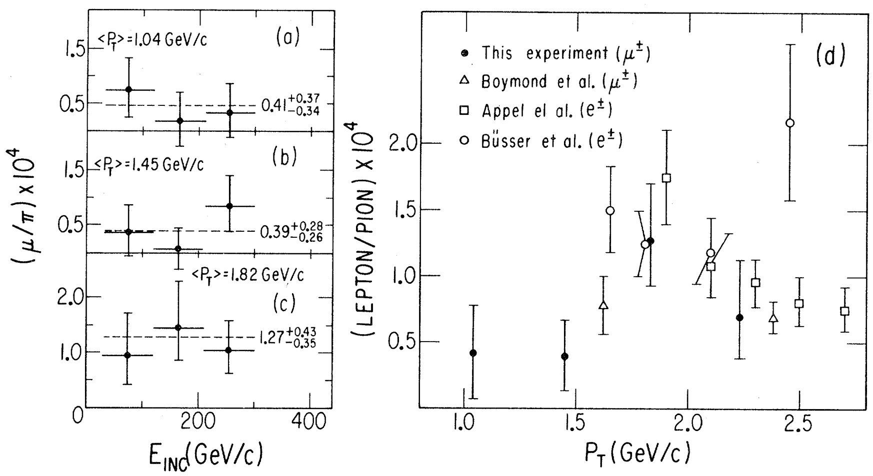

FIG. 3. (a), (b), (c) Prompt-muon/pion ratio as a function of bombarding proton energy for different intervals of muon transverse momentum. (d) Prompt-lepton/pion ratio as a function of transverse momentum. Data from this experiment have been averaged over bombarding energy.

the decay of tertiary mesons created within the hadron shield contributes negligible background. This is confirmed experimentally by the agreement between the shapes of the observed and predicted momentum spectra of Fig. 1 and by a test in which the first absorber element was changed from Heavimet (tungsten) to steel, thereby increasing the probability of such meson-decay backgrounds. Muon rates for the 2-absorption-length Heavimet absorber, and for one of stainless steel of identical geometry, are shown in Fig. 2 as the two points at the shortest decay path. The steel block corresponds to 5 times fewer radiation lengths for Coulomb scattering and to an increase in the nuclear mean free path of 80%. The rates shown in Fig. 2, after correcting for the change in detection efficiency and effective decay path, compare favorably.

Results for the ratio of the prompt-muon yield to the pion yield at the same energy and angle are shown in Fig. 3 for three intervals of bombarding energy and three muon transverse momenta. Data for μ^+ and μ^- have been combined since we observe no significant difference between them. It should be noted that the statistical significance of the prompt-muon signal is greater than indicated by the error bars of the muon/pion ratios of Fig. 3. Normalization errors are included in the ratios and increase the errors by approximately 30%. At the lowest transverse momentum the quoted errors have a significant contribution from uncertainties in the absorption lengths, detector geometry, and relative efficiency correction, while at higher momenta the error is mainly statistical.

The data of Fig. 3 show no evidence of a dependence of the prompt-muon/pion ratio on bombarding energy. A prompt muon signal is observed even in the lowest interval of bombarding energy which extends from 30 to 120 GeV.

Figure 3(d) shows the data as a function of muon transverse momentum, averaged over bombarding energy. Also shown for comparison are the data from Refs. 2–4. Care must be exercised in the detailed comparison of these experiments since each involves either a different center-of-mass energy or a different lepton type. No single experiment shows a significant structure in the prompt-lepton/pion ratio as a function of transverse momentum, although their combined effect is rather suggestive.

Conclusive demonstration of an enhancement could indicate the production and leptonic or semileptonic decay of a new short-lived state. Figure 4(a) indicates the enhancement to be expected from two-body and three-body decays of a particle of mass 3.1 GeV/c.[2] Production characteristics for the massive state were taken as $Ed^3\sigma/d^3p = A\exp(-4.5P_T)(1-|x|)^4$ and the total cross section times branching ratio for Fig. 4(a) is approximately 1.1×10^{-31} cm^2. The three-body decay was treated like the semileptonic decay of a K meson of mass 3.1 GeV/c^2. It is interesting to note that even in the three-body final state there is an enhancement, although of reduced amplitude, in the lepton/pion transverse momentum spectrum. Figure 4(b) shows the effect of different transverse momentum spectra for a

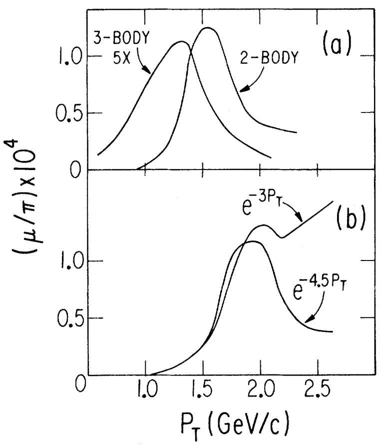

FIG. 4. (a) The μ/π ratio for muons arising from two-body and three-body decays of a mass 3.1-GeV/c^2 particle. Production and decay characteristics are described in the text. The three-body decay curve has been multiplied by 5. (b) The μ/π ratio for muons from the two-body decay of a mass 3.7-GeV/c^2 particle. Production cross sections were assumed to be of the form $\exp(-4.5P_T)(1-|x|)^4$ and $\exp(-3P_T)(1-|x|)^4$.

heavy-particle parent of mass 3.7 GeV/c^2. The total cross section times branching ratio in this case is 0.3×10^{-31} cm^2. Using the same production model described for above for Fig. 4(a), we obtain 90% confidence limits on the production cross section times branching ratio for two- and three-body decays of a mass 2.3-GeV/c^2 particle, of 4×10^{-31} cm^2 and 2×10^{-30} cm^2, respectively.

The total cross sections for the simple production parametrization described above can be compared with the measurements of ψ(3105) production and decay into μ pairs.[10] For 250-GeV/c incident neutrons and $|x_\psi|>0.24$, the reported cross section is 3.6×10^{-33} cm^2/nucleon.

Other potential sources for prompt leptons, such as lower-mass vector mesons, have been discussed in Refs. 2–4.

We gratefully acknowledge the assistance of the Internal Target Area Group and especially D. D. Yovanovitch. Significant assistance was also received from A. Benvenuti, D. Cheng, R. Piccioni, D. Reeder, J. Sidles, and A. Zylberstejn.

*Work supported by the U. S. Atomic Energy Commission and National Science Foundation. Experiment performed at the Fermi National Accelerator Laboratory.

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