Contribution of Muon Pairs to the Yield of Single Prompt Muons*

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Using data from our recent experiment on inclusive μ-pair production by 150-GeV/c protons on beryllium, we have calculated the contribution of muon pairs to the yield of single prompt muons. We find, both at 90° in the center-of-mass system and in the forward direction, that the resulting single-muon cross sections are in reasonable agreement with the existing measurements for which only one muon is detected.

Many hadron scattering experiments have observed the production of single muons from some source other than the π and K decays.[1] The effect has been measured for many kinematic regions, incident hadron energies, and target materials. All the experiments, however, have had very limited detection efficiency for the observation of a second muon. The source of the prompt muons remains unknown. Speculations have included the leptonic or semileptonic decays of some unknown particle (possibly a charmed particle), or alternatively, the production of photons, and hence μ pairs, through parton annihilation[2] or an internal bremsstrahlung mechanism.[3] Several authors have estimated the contribution of μ pairs from vector meson decays.[4] The data used for these estimates are taken from experiments performed under widely differing conditions of incident hadron energy, target materials, and systematic uncertainties. The general conclusion has been that the vector mesons could account for at most 30% of the observed signal.

In the preceding Letter, we reported results from an experiment on the inclusive μ-pair production in proton-beryllium interactions at 150 GeV/c.[5] The μ-pair mass spectrum is studied with a broad acceptance in Feynman x (x_F) and P_T for all masses above the kinematic minimum of 211 MeV/c.[2] The experiment is sensitive to μ-pair production from vector-meson decay or any other source. It is now possible to calculate the contribution of μ pairs from all sources to the single-prompt-muon cross section, using the results of one self-contained experiment.

In the following analysis, cross sections will be given per beryllium nucleus, which is the quantity directly measured. No attempt is made to extrapolate to proton-nucleon cross sections since the A dependence of the Lorentz-invariant cross section depends on both the particle mass and transverse momentum.[6] Since good measurements of the π production from beryllium are available, the prompt μ/π ratio can be deduced with no assumptions of A dependence. The production of single prompt muons has been observed from a variety of nuclear targets including beryllium.[7]

Our μ-pair studies are in the range $x_F > 0.15$ and 0 GeV/$c \leq P_T \lesssim 2$ GeV/c. In order to compare these results with the existing single-muon measurements at $x_F = 0$, the data must be parametrized to obtain a reasonable extrapolation to $x_F = 0$. As already discussed[5] we find that an extrapolation of a fit by $d\sigma/dx_F \propto (1-x_F)^c$ gives an integrated cross section which is within 10% of the value obtained by assuming that $E d\sigma/dx_F = d\sigma/dy$ is flat for $x_F < 0.15$. An extrapolation of a fit of $E d\sigma/dx_F$ by $(1-x_F)^c$ gives substantially larger cross sections at low mass since no rapidity plateau is imposed. Accordingly, we parametrize the data in terms of $d\sigma/dx_F$ for the present calculation. The results of fitting the data by the form $d\sigma/dx_F = A(1-x_F)^c$ and $(d\sigma/dP_T)/P_T \propto \exp(-bP_T)$ are given in Table I. The quality of the fits is very similar to that shown in Ref. 5 for the Lorentz-invariant form of the x_F dependence.

The contribution of μ pairs to the single-μ cross section was calculated independently for each of the sources listed in Table I. For the continuum components, $d\sigma/dM_{\mu\mu}$ was parametrized as $\exp(-5M_{\mu\mu})$ within each of the intervals, as indicated by the data. The masses of all resonances were fixed at their nominal values except the ρ which was assumed to have a Gaussian distribution of 150 MeV/c^2 full width at half-maximum. We assume that $\sigma_\rho = \sigma_\omega$. The separation of the ρ-ω signal into two components was done only to allow for the width of the ρ.

TABLE I. Parametrization of inclusive μ-pair production cross section. The x_F dependence is fitted by the form $d\sigma/dx_F = A(1-x_F)^c$. The p_T dependence is fitted by $(d\sigma/dp_T)/p_T \propto \exp(-bp_T)$.

Source	A (nb)	b $[(\mathrm{GeV}/c)^{-1}]$	c
ρ	$(4.28\pm 0.85)\times 10^3$	3.79 ± 0.09	4.32 ± 0.13
ω	$(7.6\ \pm 1.5)\times 10^3$	3.79 ± 0.09	4.32 ± 0.13
φ	$(2.2\ \pm 0.4)\times 10^3$	3.93 ± 0.27	5.57 ± 0.38
J	140 ± 42	2.08 ± 0.26	3.76 ± 0.48
Continuum (mass range)			
<0.45	$(6.2\ \pm 1.2)\times 10^4$	4.63 ± 0.15	8.25 ± 0.23
0.45–0.65	$(2.0\ \pm 0.4)\times 10^4$	4.58 ± 0.14	6.45 ± 0.22
0.65–0.93	$(4.4\ \pm 0.9)\times 10^3$	3.79 ± 0.09	4.32 ± 0.13
0.93–1.13	$(1.4\ \pm 0.3)\times 10^3$	3.93 ± 0.27	5.57 ± 0.38
1.13–2.0	$(6.4\ \pm 1.3)\times 10^2$	3.41 ± 0.85	5.10 ± 0.90

The calculation proceeded by standard Monte Carlo techniques. Muon-pair events were generated in x_F and P_T, corresponding to the cross sections given in Table I. The μ-pair state was allowed to decay isotropically in its own rest frame and events were binned on the basis of the x_F and P_T of one of the decay muons. Events were assigned a weight so that each bin accumulated the Lorentz-invariant production cross section for single muons of a given charge.

To check the calculation, a second independent computation was made using analytic techniques and numerical integration. The two calculations agreed in all respects. The sensitivity of the result to the assumption of an isotropic decay of the μ pair was tested using a $1+\cos^2\theta^*$ decay distribution. The single-μ cross section as a function of P_T, at $x_F=0$, changed by less than 10% for all P_T less than 2.5 GeV/c. An analysis of the decay angular distribution of our ρ-ω data shows that any polarization is small.[5]

To understand the sensitivity of the single-μ cross section to the P_T spectrum of the μ pairs, the parentage of single muons at fixed x_F and P_T was studied. For muons of P_T significantly larger than half the mass of the parent, the P_T of the parent is, on the average, only slightly larger than that of the μ. For example, single μ's of $P_T=1.0$ GeV/c and $x_F=0$, produced by ω decay, arose from parent ω mesons with a mean P_T of 1.2 GeV/c. Thus, for transverse momenta less than 2 GeV/c, the single-μ cross section is relatively insensitive to the P_T spectrum of the parents beyond the region of measurement.

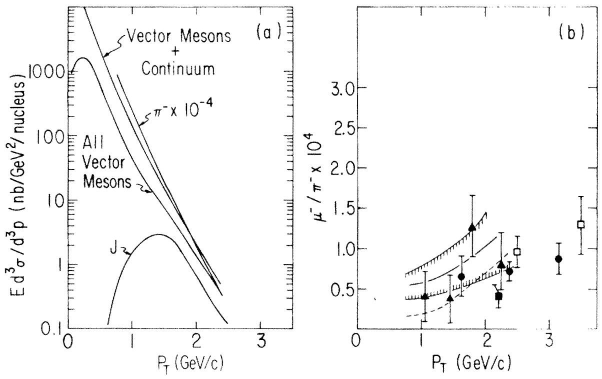

FIG. 1. (a) The Lorentz-invariant cross section for single muons at $x_F=0$ arising from μ-pairs produced in 150-GeV p + Be interactions. Also shown is the π^- cross section from beryllium. (b) The calculated μ^-/π^- ratio and comparison with the existing data at $x_F=0$. The symbols ● and □ refer to the two experiments of Ref. 7; ▲, Ref. 8; and ■, Ref. 9. The solid line and error bounds show the predicted μ/π ratio from all pair sources. The broken line is the predicted ratio for vector mesons alone.

Figure 1(a) shows the resulting single-μ Lorentz-invariant cross section as a function of transverse momentum at $x_F=0$. The curve for the π^- cross section ($\times 10^{-4}$) represents measurements from a beryllium target at 300 GeV, scaled down by about 30% using the energy dependence as a function of P_T measured in the same experiment.[6] The contribution of the vector mesons to the single-muon cross section is shown, in addition to the signal from all pair sources. The continuum contributes approximately 50% of the signal at a P_T of 1.5 GeV/c and 36% at 2 GeV/c. The contribution of $J\to\mu^+\mu^-$ to these two regions is 20% and 31%, respectively.

Figure 1(b) shows the μ^-/π^- ratio and the comparison with existing single-μ measurements.[7-9] Since the data show no difference between μ^+/π^+ and μ^-/π^-, measurements of both ratios are included. The experiments of Ref. 7 were performed at 300 GeV, Ref. 8 at a mean energy of 150 GeV, and Ref. 9 at 70 GeV. We see that the yield of single μ's from μ pairs is a good representation of the experimental data. The error in our μ/π ratio is dominated by normalization uncertainties at low P_T and is increased by the uncertainty in the μ-pair transverse momentum spectrum as the P_T increases.[10] Also shown in Fig. 1(b) is the μ/π signal arising from the vector mesons alone.

Prompt-electron measurements are not included in Fig. 1(b) since the contribution of continuum

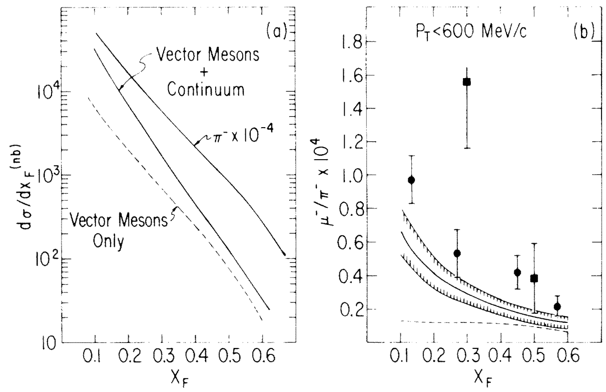

FIG. 2. (a) Cross section for single-muon production as a function of x_F, integrated over all p_T less than 600 MeV/c. The dashed line shows the predicted cross section for vector mesons alone. (b) The calculated μ^-/π^- ratio and comarison with the existing data in the forward direction. The symbol ● is the data of Ref. 13; ■, of Ref. 14.

e^+e^- pairs may be substantially different from that of μ pairs.

Figure 2(a) shows the single-μ yield in the forward direction, integrated over P_T less than 600 MeV/c, as is required for comparison with the single-muon measurements. We see that the total single-μ signal falls more quickly with x_F than pion production or the single-μ cross section from vector mesons. This follows from the steep x_F dependence of the low-mass μ-pair continuum.

The pion cross section from beryllium given in Fig. 2(a) is from a CERN proton synchrotron experiment,[11] assuming Feynman scaling. We have compared these results with a less complete set of measurements at 200 and 300 GeV[12] and find agreement to within 20%. Figure 2(b) shows the μ^-/π^- ratio as a function of x_F and the comparison with experiments in the forward direction.[13,14]

The size of the continuum signal relative to the vector mesons is significantly larger in this low-P_T region. The total μ^-/π^- signal predicted from pairs has the same x_F dependence as the single-μ measurements although it lies below them by about a standard deviation. Our result tends to support the conclusions of Kasha *et al.*,[13] that the single muons in the forward direction arise predominantly from a μ-pair source other than vector meson decays. We find, however, that the μ-pair mass spectrum is not dominated by any unusual source near 900 MeV/c^2 as suggested in Ref. 13.

Figure 3 shows the expected pair-produced single-muon signal in other kinematical regions. The errors to be associated with these curves

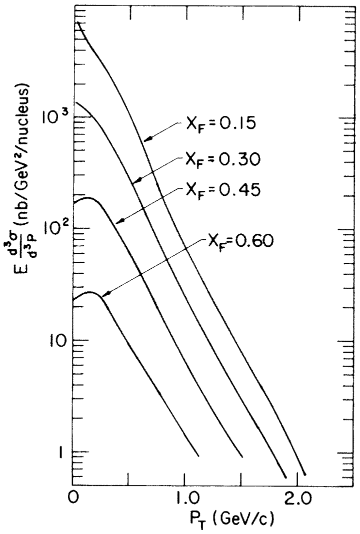

FIG. 3. Lorentz-invariant cross section for the inclusive production of single muons of a given sign from muon pairs, as a function of x_F and p_T.

can be estimated from the error bands of Figs. 1(b) and 2(b).

In conclusion, the present measurements of the prompt single muons are in reasonable agreement with the yield expected from μ pairs. In the forward direction the μ-pair continuum plays a significant role in producing the single muons.

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Structure in K^--Nucleon Total Cross Sections below 1.1 GeV/c*

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Total cross sections of K^-p and K^-d have been measured between 410 and 1070 MeV/c with high statistical precision. In addition to the well known $\Lambda(1520)$, $\Lambda(1820)$, and $\Sigma(1769)$, we confirmed the presence of the $\Lambda(1692)$ and the $\Sigma(1670)$. We have also observed several structures which could be Y^* resonances: $\Lambda(1646)$, $\Lambda(1735)$, $\Sigma(1583)$, $\Sigma(1608)$, $\Sigma(1633)$, and $\Sigma(1715)$.

Meson-nucleon total-cross-section measurements below incident momenta of a few GeV/c have, in the past, provided valuable information on new baryon resonances. A structure in the momentum dependence of the cross section has often been the first indication of a resonance and has also provided a number of its parameters. In addition, such measurements are a very important constraint for phase-shift analyses from which resonances, not directly observable, can be found and have their parameters determined.

The K^--nucleon system in the mass range from 1500 to 1800 MeV is very rich in Y^* resonances; there are claims for about a dozen resonances with status varying from "good, clear and unmistakable" to "weak."[1] Earlier total-cross-section measurements in this region[2-4] cover only limited momentum ranges (giving rise to possible normalization problems between experiments) and do not have the experimental accuracy currently attainable.

The present experiment was part of a series of measurements[5,6] made below 1.1 GeV/c at the Brookhaven National Laboratory alternating gradient synchrotron to give significantly improved data in an interesting momentum region. They were carried out in order to search for new structures and also to provide considerably more accurate data than previously available for phase-shift analyses. Preliminary results of the present data on K^-p and K^-d cross sections have been reported earlier.[7]

The experiment used a standard transmission method with special precautions taken to avoid the problems inherent in such a technique at low momenta; the experimental details and method of data analyses have been given elsewhere.[5,6] In this experiment, the hydrogen and deuterium targets were 3 ft long. Corrections to the data for kaon decay, which could be as large as 20% at low momenta, were verified experimentally at two different momenta by measuring cross sections with varying distances between the target and transmission counters.[5] In evaluating the Coulomb-nuclear interference correction, the slopes of the elastic differential cross sections were obtained from interpolations of the published experimental data.[8,9] The ratios between the real and imaginary parts of the forward-scattering amplitudes for protons were taken from experimental data[10] and were assumed to be the same for neutrons. The kaon momenta were corrected for energy loss in the target. Experimental resolution caused mainly by this energy loss was unfolded from the data by an iterative procedure; the correction was typically about 0.2% and never exceeded 2%.

Statistical errors on the hydrogen cross sections varied from ± 0.23% at high momenta to ± 0.65% at 574 MeV/c and to ± 2.5% at the lowest momentum; the corresponding deuterium percentage errors were about half as much. Rela-