OBSERVATION OF PROMPT SINGLE MUONS AND OF MISSING ENERGY ASSOCIATED WITH $\mu^+\mu^-$ PAIRS PRODUCED IN HADRONIC INTERACTIONS*

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ABSTRACT

In a study of interactions of 400 GeV protons in a totally absorbing iron calorimeter we report two observations indicating the hadronic production of heavy short-lived weakly decaying particles. First we have observed a prompt muon signal in the region $.8 < p_t < 2.5$ GeV/c. The rate is comparable in magnitude to the prompt 2μ rate in the same kinematic region. In addition to detecting $\mu^+\mu^-$ events arising from electromagnetic sources (e.g., $\rho \rightarrow \mu^+\mu^-, \psi \rightarrow \mu^+\mu^-$ etc.) we have observed $\mu^+\mu^-$ pairs associated with a significant amount of missing energy indicative of final state neutrinos. Interpreting these data as production of $D\bar{D}$ pairs followed by single or double muonic decays leads to a model dependent estimate of total production cross-section of order 15 μb.

INTRODUCTION

The hadronic production of charmed particles had recently received considerable experimental and theoretical attention. QCD calculations predict cross-sections in the range 1-30 μb in 400 GeV p-N interactions[1], with gluon fusion probably giving the dominant contribution. Previous searches for charm production have produced widely varying results[2-6], ranging from upper limits of $\sim$1 μb/nucleon[2,3] at 400 GeV to a recently reported signal of $\approx$150 μb at the ISR[5]. The prompt neutrino signal reported by the CERN beam dump experiments[6], if interpreted as a charm signal, corresponds to a production cross-section of 25-50 μb/nucleon (assuming linear A dependence)[7].

One of the cleanest signatures of charm production would be the observation of a prompt single-muon signal, since the branching ratio of charm into $\mu\nu$ + hadrons is large ($\sim$10%) and other sources of prompt single muons are negligible. Several experimental groups[2,8,9] have reported sizable prompt muon production, but previously only two[2,9] have attempted to separate 1-μ from 2-μ events (the latter are due primarily to electromagnetic rather than weak decays). The results of both of these groups were consistent with all the prompt muon signal originating from 2-μ events, but allowed a sizable single muon signal.

PROMPT SINGLE MUONS

We report here on the observation of a prompt 1-μ signal in the moderately high p_t ($0.8<p_t^{\mu^+}<2.5$ GeV) and low x_F ($10<E^{\mu^+}<60$ GeV) region produced by 400 GeV p-N interactions. We find approximately equal production cross-sections for 1-μ and 2-μ final states in this kinematic region. We also present evidence for the observation of missing energy (indicative of final state neutrinos) in association with hadronically produced $\mu^+\mu^-$ pairs, and relate it to the observed single muon signal.

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The experiment was performed in the Fermilab N5 beam with 400 GeV protons at typical intensities of 3-5 10^5/sec. The primary elements of the detector (Fig. 1) were a fine-grained target-calorimeter of variable density[10)] (energy resolution of 3.5% at 400 GeV), a muon identifier (MI), and a toroidal muon spectrometer[11)].

The data reported here were taken with a high-p_t trigger, which required a coincidence of both a beam and a muon trigger component. The muon component required the muon to remain in the same quadrant throughout the toroid system by requiring the appropriate coincidence of counters C, S2, ACR, T4 (which were divided into quadrants) and S1, T2, T3, MV (divided into half-planes). This requirement preferentially selected muons with high p_t ($p_t^{\mu^+} > .8$ GeV).

The beam component required an incident proton to pass through counters B0 and B1 (7.6×7.6 cm and 5.1×5.1 cm) and to interact within the first 10 plates of the calorimeter. To reject any background from upstream interactions, triggers were vetoed by the presence of any additional particles in the beam or halo counters within 95 nanoseconds of the trigger. Further beam information was provided by the pulse height of the trigger counters and by the incident proton's trajectory and momemtum, as measured by a spectrometer immediately upstream of the calorimeter. Interactions satisfying the beam trigger alone were scaled, and one out of each 2^{16} was recorded to provide a control sample of interactions without any muon requirement.

In the data analysis, software cuts were made to insure that the muon trigger counters were associated with a good trajectory, that the μ^+ enter the toroid system at least 17.5 cm from the axis (outside of the hole), and that the interaction point lie between plates 1 and 8 of the calorimeter. The muon trigger acceptance after all these cuts was greater than 50% over the range $1.0 < p_t^{\mu^+} < 2.5$ and $20 < E^{\mu^+} < 60$ GeV.

The majority of muons which triggered the apparatus were due to pion and kaon decays. This background was measured by uniformly expanding the first 25 plates (1 meter of steel) of the calorimeter, thereby proportionally increasing the mean path length and decay probability of hadrons in this region. Most of the hadrons decaying downstream of this region were produced by secondary or tertiary interactions, and consequently gave decay muons that were generally too low in energy to satisfy the trigger.

The experiment collected data at three different densities (keeping the mean interaction point fixed in space): fully compacted, expanded by a factor of 1.5, and expanded by a factor of 2. The mean calorimeter density in the compacted configuration was 3/4 that of steel due to the gaps (1.3 cm) between plates. After all software cuts, the rates in each density configuration were normalized to the beam trigger rates and plotted as shown in Fig. 2. As expected, the 2-μ rate is flat, and the 1-μ rate shows a linear increase with the effective pion interaction length. The 1-μ slope measures the rate from non-prompt decays, and the intercept of $(10.5 \pm .5)10^{-6}$ at infinite density is the raw prompt 1-μ signal.

To obtain the true prompt single muon rate, the raw prompt 1-μ rate had to be corrected for several background sources:

a) $\mu^+\mu^-$ events with a low energy μ- which ranged out in the calorimeter or muon identifier. A Monte-Carlo calculation using the measured $\mu^+\mu^-$ distributions gave a correction of $10 \pm 2\%$ (systematic errors included) of the raw prompt 1-μ signal. This component was subtracted from the 1-μ signal and added to the 2-μ signal.

b) Muons from decays of pions and kaons in the unexpanded part of the calorimeter (after plate 25). A Monte-Carlo simulation of the hadron shower, which reproduced the mean shower profile measured in the experiment, gave a correction of 8±3% of the measured decay rate[12]. This corresponds to 16±6% of the prompt 1-μ signal.

c) A subtraction of 20±10% of the prompt 1-μ signal due to second order variation in the acceptance with density. These arise because, although the mean interaction point stays fixed, multiple scattering effects and production by secondaries move downstream when the calorimeter is expanded.Since the toroid hole subtends a larger angle for particles originating downstream, this yields a reduction of 4±2% in the acceptance of the expanded relative to the compacted configuration. This correction was obtained from the $\mu^+\mu^-$ events (which should be constant with density).

After all corrections, the measured prompt 1-μ rate was $(5.8\pm1.5)\times10^{-6}$ per incident proton and the 2-μ rate was $(5.9\pm.2)\times10^{-6}$; the errors are largely systematic. A natural explanation of this single muon signal would be production and subsequent decay via leptonic mode of new heavy hadrons, the most likely candidates being the charm particles. That same mechanism would also require a production (at a lower rate) of a pair of charged muons, both of which originate from the decay of charm particles. The muons from this process would have to be associated with a missing energy due to companion neutrinos emitted in the decay.

TWO PROMP MUONS WITH MISSING ENERGY

The total observed energy spectrum for $\mu^+\mu^-$ events ($E_{tot}=E_{\mu^+}+E_{\mu^-}+E_{calorimeter}$) is shown in Fig. 3. The dashed curve shown for comparison is the E_{tot} spectrum exhibited by beam interactions without final state muon. There is a pronounced enhancement of missing energy events for $m_{\mu^+\mu^-}<2.4$ GeV. We observe 227 $\mu^+\mu^-$ events with missing energy in excess of 45 GeV. An estimate of the double π,K decay background is provided by the 5 observed like sign dimuon events with large missing energy. Monte Carlo calculation of $K\bar{K}$ production and double decay also yields a background of 5 events. Also, since the toroid spectrometer is instrumented with acrylic calorimetry counters, we can rule out catastrophic muon energy loss in the steel as significant source of background. We conclude that all backgrounds are unlikely to contribute more than 10% of the observed $\mu^+\mu^-$ with missing energy signal.

INTERPRETATION

To estimate a charm production cross-section from these data, we have assumed that all the signal comes from the semileptonic decays $D\rightarrow K\mu\nu$ (60%) and $D\rightarrow K^*\mu\nu$ (40%) with a total semileptonic branching ratio of 8%. The inclusive D cross-section was assumed to increase linearly[13] with the atomic number A of the nucleus and was parameterized as

$$E\,\frac{d^3\sigma}{dp^3} = C\,(1 - x_F)^{\beta}\, e^{-\alpha p_t} \quad \text{(for inclusive D production)} \qquad (1)$$

The single muon data were consistent with values in the range α=2.0-3.5 GeV^{-1} and β>3. Varying α and β over these allowed ranges yields charm cross-sections in the range 15-75 μb/nucleon. For β=5 and α=2.5, the acceptance for the produced μ^+'s was 2.5% and the cross-section for D production was $\sigma_{D\bar{D}}$ = 36±9 μb/nucleon. This model, in which the two charmed states are uncorrelated gives an acceptance of 0.14% for the $\mu^+\mu^-$ events with 45 GeV of missing energy and yields a charm cross-section of 22±8 μb. However, the $\mu^+\mu^-$ mass and momentum distributions do not fit this model.

In order to include the expected correlation between the D and $\bar{D}$ state we assume a

$D\bar{D}$ model production model

$$E \frac{d^3\sigma}{dp^3} = \frac{C}{M^3} (1 - x_F)^\beta e^{-\alpha p_t} e^{-M/\sqrt{s}} \text{ (for } D\bar{D} \text{ production)} \quad (2)$$

and calculated the fraction of $D\bar{D}$ double muonic decays which satisfy our trigger requirement, give 2 μ's that pass the muon cuts, and yield a measured missing energy in excess of 45 GeV. Here the kinematic variables in the above cross-section equation refer to the composite $D\bar{D}$ system (and $\sqrt{s}$=27.4). The acceptance was rather insensitive (to ±30%) to variations in α between 1.5 and 3.0 GeV^{-1} and γ between 0.0 and 17.5. For α=2.23, β=2.96 and γ=14.9 we obtain an acceptance of 0.39% yielding a charm cross-section of 8±3 μb. Using this same model we obtain a charm cross-section of 24±5 μb from the single muon data. Changing β from 2.96 to 6.0 changes the $\mu^+\mu^-$ acceptance from 0.39% to 0.24%. In general, the 2μ with missing energy data yield lower cross-sections than the prompt single muon data. We are presently investigating various distributions that will bring the two sets of data into better agreement, and still fit the measured distributions. (For example, making β larger appears to help.) Besides finding better parameters, we are investigating whether we are using an improper production mechanism, e.g. improper correlation between the D and $\bar{D}$ state, the possibility of different branching ratios for the charge and neutral states, a possible contribution from charmed baryon production etc. Until these model uncertainties are resolved by more fits to the experimental distributions, charm cross sections between 7 to 70 μb are consistent with the data. Also, the next run of Fermilab experiment[14] E595, which measures prompt single muons over a larger kinematic range, will help resolve the model uncertainties.

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12) Recent measurements of downstream decays, using a similar trigger in a modified version (Fermilab E595) of this experiment, have confirmed this Monte-Carlo estimate.

13) We have used a total inelastic ρ-Fe cross section of 690 mb which is 12.4 mb/nucleon (A.S.Carrol et al., Phys. Lett. 80B, 319 (1979).

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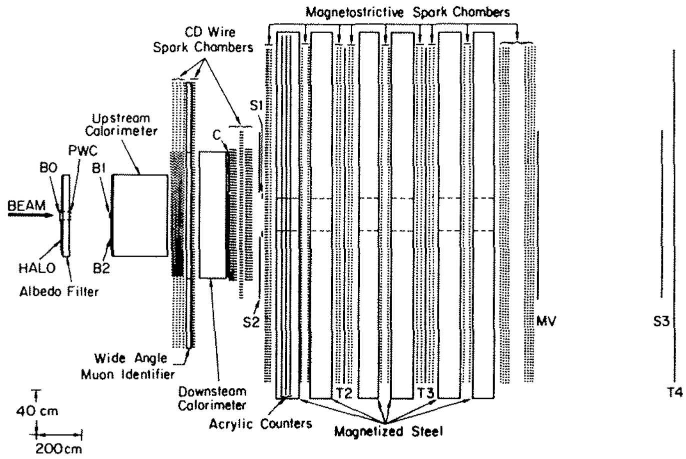

FIGURE 1

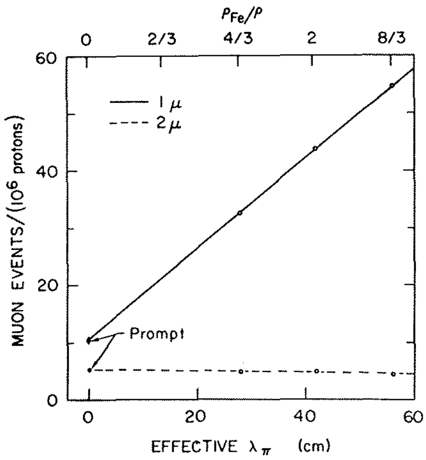

FIGURE 2

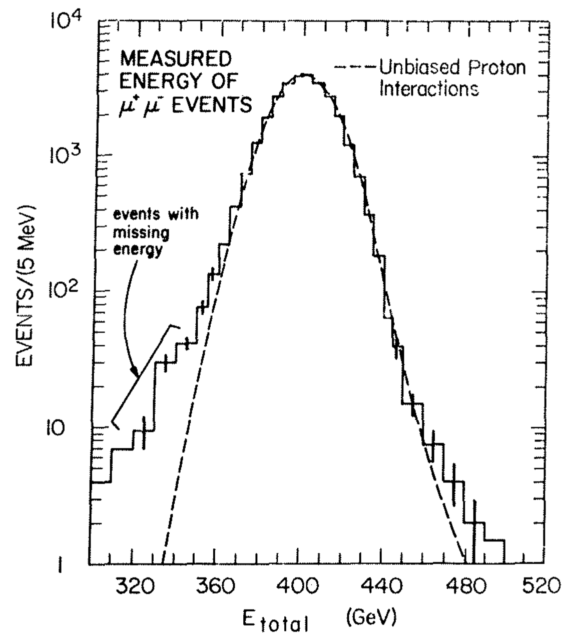

FIGURE 3

FIGURE CAPTIONS

1. The experimental setup.
2. The raw 1μ and 2μ experimental rates per 10^6 protons versus inverse density. After background subtractions the prompt 1μ and 2μ rates are equal.
3. The number of $\mu^+\mu^-$ events versus the total observed energy ($E_{total}=E_{\mu^+}+E_{\mu^-}+E_{calorimeter}$).