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SEARCH FOR POSSIBLE SIGNATURES OF BOTTOM MESON PRODUCTION IN p-Fe INTERACTIONS AT 400 GeV/c*

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ABSTRACT

We have searched for evidence of bottom quark state production in p-Fe interactions at 400 GeV/c by looking for multi-muon final states. Muons in such final states could come from $B \to \Psi \to 2\mu$ decay accompanied by a muonic decay of $\overline{B}$ (or $\overline{B} \to \overline{D} \to \mu$ chain) or from a combination of B and D muonic decays. Assuming a 10% branching ratio for $B \to \mu X$, a search for several specific decay modes yields an upper limit for the B production cross-section of $\lesssim 50$ nb/nucleon.

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Recently there has been reported evidence (1) for the production of a new heavy state in π^-N interactions at 150 and 175 GeV/c. The mass of this state, 5.3 GeV, and the observed decay mode (2), $\psi K\pi$, make it very tempting to associate this new possible state with the predicted B meson, i.e., a postulated bound state of a b and $\bar{d}$ quark. Furthermore, the size of the cross-section, about 200 nb based on reasonable assumptions about the branching ratio, appears to be very close to recent theoretical estimates [3]. These same theoretical estimates predict an even larger cross-section for 400 GeV p-p interactions.

In this communication, we report on the search for multi-muon final states in p-Fe interactions at 400 GeV/c which could be possible signatures of $B\bar{B}$ production and decay. The apparatus used in this work has been described in detail previously [4]. Its principal elements are a variable density target-calorimeter which measures the total hadronic and electromagnetic energy to $\pm$ 3.5% at 400 GeV, an instrumented muon identifier, and a large solid angle iron toroidal muon spectrometer. The important characteristics of the apparatus are the large muon acceptance, the ability to determine missing neutrino energy, and the high density of the target calorimeter which strongly suppresses background muons from π and K decays.

We have searched for three particular signatures of $B\bar{B}$ production and decay:

1) $pN \rightarrow \psi\mu X$, i.e., a final state containing 3 muons, 2 of which reconstruct to a ψ mass (2.6 GeV < M < 3.6 GeV) and arise from $\bar{B}(B) \rightarrow \psi X$ decay, and the third one comes from $\bar{B}(B) \rightarrow \mu\nu X$, or $\bar{B}(B) \rightarrow \bar{D}(D)X$ with $D(\bar{D}) \rightarrow \mu\nu X$.

2) $pN \rightarrow \mu\mu\mu X$, a 3μ final state without any mass restriction arising from the following decay chain (or its charge conjugate):

$B \to D\mu^- \nu$ with $D \to \mu^+ \nu X$

$\overline{B} \to \overline{D}\mu^+ \nu$ with $\overline{D} \to$ hadrons

or, alternatively,

$B \to D\mu^- \nu$ with $D \to \mu^+ \nu X$

$\overline{B} \to \overline{D}X$ with $\overline{D} \to \mu^- \nu X$

3) $pN \to \mu^+ \mu^+ X$, arising from

$B \to DX$ with $D \to \mu^+ \nu X$

$\overline{B} \to \overline{D}\mu^+ \nu$ with $\overline{D} \to$ hadrons

The experiment used a relatively loose trigger, requiring a μ^+ of $p_t \geq 0.8$ GeV/c. Each muon in a multi-muon event was required to have enough transverse momentum to miss the hole in the toroids, to traverse the first toroid ($E_\mu > 7.5$ GeV), and to intersect at least 5 chambers in the spectrometer. Background multi-muon events arising from an extra muon unassociated with the interaction were eliminated by running the experiment at moderately low intensities (5×10^5 protons/sec) and vetoing triggers if there were any additional beam particles in beam or halo counters within ± 95 nsec of the trigger. All muons were required to be in time with the interaction and to extrapolate to a vertex inside the calorimeter. The probability for other background muons (primarily from π and K decay in the hadron shower) was directly measured by triggering the apparatus on random proton interactions without any muon requirement. In addition, the contribution of π- and K-decays to multi-muon events was checked by comparing multi-muon rates at different calorimeter densities.

The size of these background subtractions can be substantially reduced by applying cuts to the data. Since muonic decays of the B produce high p_t muons ($\langle p_t \rangle \approx 1.5$ GeV/c) and D decays produce moderately high p_t muons ($\langle p_t \rangle \approx .5$ GeV/c), requiring high p_t

minimizes the contribution of π- and K-decay muons to the muti-muon signal. Backgrounds may also be reduced by the requirement of large missing energy carried away by the final state neutrinos.

The efficiencies for the detection of specific final states were calculated using the following assumptions about $B\bar{B}$ production and decay modes:

a) B's are produced via the reaction

$$p + Fe \rightarrow B + \bar{B} + \ldots$$

with the invariant cross section given by

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{M^3}(1 - x_F)^{\alpha} e^{-\beta p_t} e^{-\gamma M/\sqrt{s}}$$

where x_F, p_t, and M refer to the compound $B\bar{B}$ system (with $M \geq 10.6$ GeV), and $\alpha = 3.0$, $\beta = 2.2$, and $\gamma = 15$.

b) the cross-section follows linear A dependence.

c) the leptonic decay mode of the B proceeds via

$$B \rightarrow D\mu\nu$$

d) the nonleptonic decay mode of the B proceeds via

$$B \rightarrow D\pi\pi$$

e) all the ψ final states resulting from the B decay are represented by

$$B \rightarrow \psi K\pi$$

Our detection efficiencies are only mildly dependent on these production and decay assumptions. However, the determination of $B\bar{B}$ production cross-sections from multi-muon signatures is obviously dependent on the branching ratio assumptions. The assumptions used here are $B \rightarrow \psi X = 3\%$, $B \rightarrow D\mu\nu = 10\%$, $B \rightarrow DX = 100\%$, and $D \rightarrow \mu\nu K$ (or K^*) = 8% [5] (with a K/K^* ratio of 1.5). We have assumed, for simplicity, that the charged and neutral states have equal semileptonic branching ratios. If the muonic branching ratio of the B^+ is greater than that of the B^0 in analogy with the recently observed (6) difference between D^+ and D^0 branching ratios, and the 3 body semileptonic decays of the B are the dominant ones then the 3μ final states would be suppressed due to the sign correlation between B and D in the cascade decays. The branching ratios to $\psi\mu$ and $\mu^+\mu^+$ are relatively insensitive to that assumption.

The trigger efficiencies, as well as the final acceptance after all analysis cuts on the muons, were calculated for each final-state category using a Monte Carlo simulation of the apparatus. These efficiencies, with the assumed branching ratio into each final state, are summarized in Table I. We have included, as subcategories, the effects of additional cuts in p_t and missing energy which serve to enhance signal/background. The sensitivity (i.e., partial cross-section per detected event), given in the fourth column, is the product $\sigma_{pN}/(N_p\varepsilon)$, where σ_{pN} = 13 mb/nucleon is the p-N cross-section on iron nuclei [7], $N_p = 1.25 \times 10^{10}$ is the total number of interacting protons (after dead time correction and cuts), and ε is the acceptance for detecting the final state muons. The inclusive $B\bar{B}$ cross-section per event in the last column is obtained from the partial cross-section/event using the branching ratio in column 5.

Table II summarizes the number of detected events in each category, the estimated background, and the resulting signals. Only data from the compacted density are used here, since backgrounds are smaller. Backgrounds arise from a single uncorrelated muon accompanying a ψ, $\mu^+\mu^-$, or μ^+ final state, and were calculated from the production rate of single muons which satisfied all analysis requirements. A μ^+ rate of $(2.9 \pm .6) \times 10^{-4}$/interaction and a μ^- rate of $(6.0 \pm 1.0) \times 10^{-4}$/interaction were measured [8] in this experiment using the sample of random proton interactions taken throughout the run. The backgrounds in coincidence with a ψ or $\mu^+\mu^-$ were estimated to be ≈15% smaller because of the reduction in hadron shower energy due to the production of the dimuon pair. In the case of $\psi\mu$ final states, for example, the background of 2.9 events is the product of 3848 recorded ψ's times an estimated rate of 7.6×10^{-4}/interaction for an accompanying uncorrelated μ^+ or μ^-.

As a check of these background estimates, multimuon events taken at three different densities are compared in Figure 1. The curves give the shape expected if the extra muons were entirely due to π and K decay backgrounds. It is evident that most, if not all, of the events are due to this background.

None of the categories recorded in Table II shows any evidence of a statistically significant positive signal (with the possible exception of the single event which survives the p_t cut in category 1a). We conclude from the limits in columns 6 and 7 that $\sigma_{B\bar{B}} \leq 50\text{nb}^{(9)}$. In analogy to the ratio $\sigma_{C\bar{C}}/\sigma\psi \simeq 100$ for charm (10) one might expect that $\sigma_{B\bar{B}}/\sigma\Upsilon \simeq 100$. The measurements $\sigma\Upsilon \cdot BR(\Upsilon \to \mu\mu) = (0.5 \pm 0.13)$ pb/nucleon (11) for 400 GeV protons and the branching ratio $BR(\Upsilon \to \mu\mu) = (2.3 \pm 1.4)\%$ (12) would then indicate $\sigma_{B\bar{B}} \simeq 2$ nb/nucleon. Our 50 nb limit is quite consistent with this estimate as well as with the estimate of 10 nb obtained from QCD calculations [13]. However, the estimates from the gluon vector-dominance model [13] of $B\bar{B}$ production, which are consistent with the measurements of Barate et al. of $\sigma(\pi^- N \to B\bar{B}X) = 200$ nb for 150 GeV π^-, predict $\sigma(pN \to B\bar{B}X) = 850$ nb for 400 GeV protons (with an uncertainty of a factor of 2). This is a factor of 17 greater than the range allowed by our data.

In the case of $\psi\mu$ final states we can make a more direct comparison with the data of Barate et al. [1]. One would expect $\sigma(B\overline{B} \to \psi K\pi) \simeq 3\sigma(B\overline{B} \to \psi\mu)$ since $BR(B \to \psi K\pi)/BR(B \to \psi X) \simeq 0.5$ [2], and $[BR(B \to \mu X) + BR(B \to DX)BR(D \to \mu X)] \simeq 0.18$. Barate et al. [1] quote $\sigma_B \cdot BR(B \to \psi K\pi) = 2$ nb. This implies [14] $\sigma_{B\overline{B}}\ BR(B\overline{B} \to \psi\mu) \cdot BR(\psi \to \mu\mu) = 90$ pb (using $BR(\psi \to \mu\mu) = 0.07$), for 150 GeV π^-, which is larger than our measurements of $(12\ ^{+30}_{-12})$ pb and $(28\ ^{+50}_{-28})$ pb for 400 GeV protons (see Table II). This difference may, of course, be due to the difference in incident particle. If this is the case, the data disagree with the prediction [15] that $\sigma(pN \to B\overline{B})$ at 400 GeV should be larger than $\sigma(\pi^- N \to B\overline{B})$ at 150 GeV.

In conclusion, we have searched for three multi-muon signatures of hadronic $B\overline{B}$ production in 400 GeV proton interactions, and have obtained upper limits of ≤ 50 nb, which is considerably smaller than the prediction of the gluon vector-dominance model. These limits are also smaller than recent experimental indications of $\sigma_{B\overline{B}} = 200$ nb in 150 GeV π^- interactions. The backgrounds in the multi-muon signature are small and indicate that, with additional data, a signal on the order of 10 nb (predicted by QCD) may be observable.

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(8) The difference between μ^+ and μ^- rates was due to acceptance; low energy μ^+'s were focussed into the toroid hole and then failed the analysis cuts.

(9) If the model we use were rigorously correct we could quote the lowest number in column 7 as the 90% confidence limit. To allow for a certain sensitivity to the production and decay assumptions we prefer to quote a more conservative value of 50 nb. The limit could, of course, be larger if the branching ratios turned out to be lower than the ones assumed in this paper.

(10) We have used our previous measurements (see reference (4)) of σ_{charm} = 25μb/nucleon and $\sigma_\psi \cdot BR(\psi \to \mu\mu)$ = 17 nb with $BR(\psi \to \mu\mu) = .07$.

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(14) $\sigma_B \cdot BR(B \to \psi K\pi)$ = 2 nb implies $\sigma_{B\overline{B}} \cdot BR(B\overline{B} \to \psi K\pi)$ = 4 nb.

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Table 1

CALCULATED ACCEPTANCE and SENSITIVITY
for
$B\bar{B}$ DECAY FINAL STATES

	Final State	Trigger Acceptance	Acceptance After Cuts	$BR \cdot \sigma_{B\bar{B}}$ Per Event	BR	$\sigma_{B\bar{B}}$ Per Event
1a.	$\Psi\mu$	65%	9.8%	11 pb	7.6×10^{-4}	14 nb
b.	$\Psi\mu, P_t^{\mu} > 1.4$ GeV	65%	3.4%	31 pb	7.6×10^{-4}	41 nb
2a.	3μ	43%	3.7%	28 pb	2.9×10^{-3}	9.7 nb
b.	3μ, $E_{miss} > 30$ GeV	43%	2.4%	43 pb	2.9×10^{-3}	15 nb
3a.	$\mu^+\mu^+$,	37%	6.1%	17 pb	8.0×10^{-3}	2.1 nb
b.	$\mu^+\mu^+$, $E_{miss} > 30$ GeV	37%	2.5%	42 pb	8.0×10^{-3}	5.2 nb

Table 2

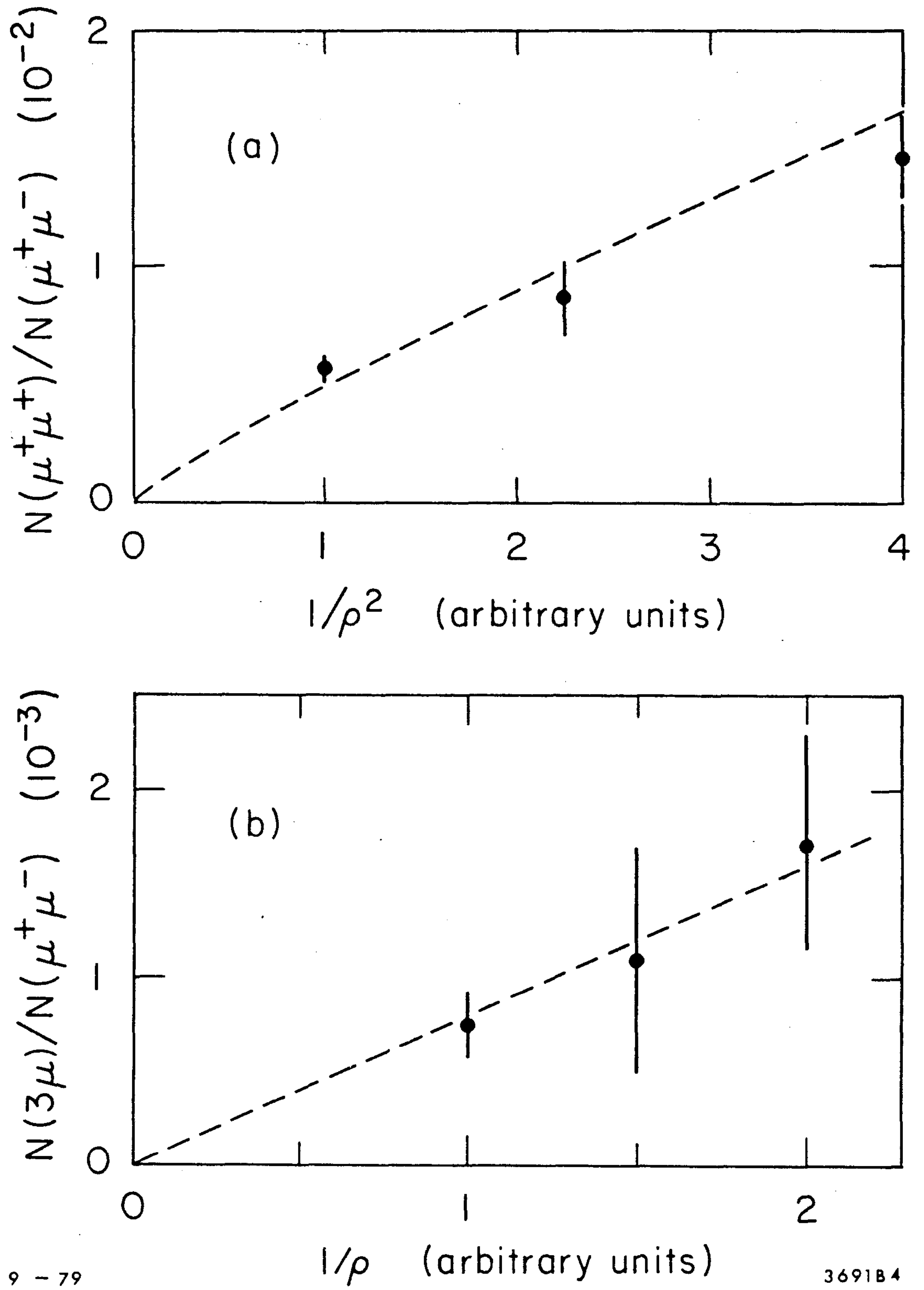
Number of Events and Cross Section Limits

for each

$B\bar{B}$ Decay Final State

	Final State	Number of Events	Calculated Background	Events	$BR\cdot\sigma_{B\bar{B}}$ (pb)	$\sigma_{B\bar{B}}$ (nb)	σ_{BB} 90% C.L.(nb)
1a.	$\psi\mu$	4	2.9 ± 0.4	$1.1^{+2.7}_{-1.6}$	12^{+30}_{-12}	15^{+38}_{-15}	<70
b.	$\psi\mu_\mu$ with $p_t^\mu > 1.4$ GeV/c	1	.1 ± .07	$.9^{+1.6}_{-1.0}$	28^{+50}_{-28}	37^{+66}_{-37}	<150
2a.	3μ	23	21 ± 3	$2.0^{+6.2}_{-5.2}$	56^{+174}_{-56}	19^{+60}_{-19}	<90
b.	3μ with $E_{miss} > 30$ GeV	1	1.0 ± .5	$0^{+1.6}_{-1.1}$	0^{+69}_{-0}	0^{+80}_{-0}	<50
3a.	$\mu^+\mu^+$	87	83 ± 19	4±21	68^{+360}_{-68}	8^{+44}_{-8}	<75
b.	$\mu^+\mu^+$ with $E_{miss} > 30$ GeV	7	5.3 ± 1.2	$1.7^{+3.4}_{-2.5}$	71^{+140}_{-71}	9^{+18}_{-9}	<40

Figure 1. The observed rates of $\mu^+\mu^+$ events (a) and of 3μ events (b) as a function of target density. The dashed lines are the rates expected if all events are due to background from coincidental π or K decays.



(a)
$N(\mu^+\mu^+)/N(\mu^+\mu^-)$ (10^{-2})
0
1
2
0
1
2
3
4
$1/\rho^2$ (arbitrary units)
(b)
$N(3\mu)/N(\mu^+\mu^-)$ (10^{-3})
0
1
2
0
1
2
$1/\rho$ (arbitrary units)
9 - 79
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Fig. 1