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**THE PRODUCTION OF BEAUTY PARTICLES IN $\pi^- - \text{U}$ INTERACTIONS
AT 320 GeV ENERGY**

(Dedicated to the memory of P. Musset)

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ABSTRACT

$B\bar{B}$ production in π^- uranium interactions has been observed at 320 GeV beam energy looking at events with three muons in the final state.

The cross-section is found to be $\sigma_{B\bar{B}} = 4.5 \pm 1.4 \pm 1.4$ nb per nucleon (for a linear A-dependence) or $\sigma_{B\bar{B}} = 17.6 \pm 5.5 \pm 5.5$ nb per nucleon (assuming $A^{0.75}$ dependence). An estimate of x_F distribution is given.

Since the discovery of the Υ resonance [1] the search for $B\bar{B}$ meson pairs produced in hadronic interactions has been performed in fixed-target experiments [2] as well as at the CERN Intersecting Storage Rings (ISR) [3] and more recently at the CERN Super Proton Synchrotron (SPS) $p\bar{p}$ Collider [4]. After a series of negative results in the fixed-target experiments carried out at the CERN-SPS and at FNAL, the first evidence of hadroproduction of $B\bar{B}$ pairs was the observation of a single event identified in a nuclear emulsion target [5].

In this letter we present evidence of production of $B\bar{B}$ pairs in π^- -uranium interactions at a beam energy of 320 GeV. The signal is found among events of the type

$$\pi N \rightarrow 3\mu + X ,$$

resulting from the $B\bar{B}$ semi-leptonic decay chains:

$$B \rightarrow \mu^- + D (\rightarrow \mu^+ + X) + X$$

$$\bar{B} \rightarrow \mu^+ + \bar{D} (\rightarrow \mu^- + X) + X .$$

Owing to the large B meson mass (≈ 5 GeV), the muons coming from B decays have a large transverse momentum (p_T) and are accompanied by energetic neutrinos. Therefore high- p_T muons and a large 'missing energy' were used for background rejection.

A detailed description of the apparatus is given elsewhere [6]; here we summarize its main features. The experimental set-up comprised a dump calorimeter followed by a magnetic spectrometer (fig. 1). The momenta of the muons emerging from the dump were measured by the magnetic spectrometer. The missing energy (E_{miss}) was measured by comparing the beam energy (E_{beam}) with the sum of the hadronic energy measured in the dump calorimeter (E_{cal}) and the energies of the outgoing muons (E_{μ}) measured in the spectrometer:

$$E_{\text{miss}} = E_{\text{beam}} - E_{\text{cal}} - \Sigma E_{\mu} .$$

The dump calorimeter, consisting of a uranium/scintillator sandwich, was designed to operate in high-rate conditions. At 320 GeV, data were usually taken with a beam intensity of $\approx 6 \times 10^6$ π per burst (1 burst = 2.4 s), giving a calorimeter energy resolution of $\sigma_E/E \approx 4\%$. A total of $\approx 7 \times 10^{11}$ π^- were dumped during the whole period of data taking.

The dump calorimeter was constructed so that it could be expanded easily in order to vary its mean density (ρ).

The trigger system accepted events with two or more muons in the spectrometer and a value of E_{cal} smaller than a defined threshold (usually $E_{\text{cal}} < 280$ GeV). Using this dimuon trigger $\approx 2.2 \times 10^7$ events were recorded on tape, corresponding to $\approx 5.5 \times 10^{11}$ interactions in the dump. After off-line analysis requiring at least two reconstructed muons in the spectrometer, a minimum muon momentum of 15 GeV/c and $E_{\text{cal}} \geq 80$ GeV, the following numbers of events remain

$$\mu^+ \mu^- \approx 3.7 \times 10^6$$

$$\mu^+ \mu^+ \approx 8 \times 10^3$$

$$\mu^- \mu^- \approx 17 \times 10^3$$

$$\geq 3\mu = 5589 .$$

At this point a graphical representation of each trimuon event was examined and 1889 events were rejected. Most of these events belonged to one of two categories:

- i) events with two muons and an additional track fabricated by the off-line spectrometer algorithm;
- ii) events with two muons and a third track caused by a ‘punch-through’ pion emerging from the dump and identified by its subsequent interaction.

For each of the remaining 3700 trimuon events, one of the two like-sign muons was selected at random. The sum of E_{cal} and the energy of this muon was required to be less than 260 GeV. This cut was applied in order to permit the comparison between the trimuon events and the background estimate without any bias introduced by the trigger. In fact the E_{cal} cut in the trigger has a different effect on trimuon events and on the dimuon events used in the background estimate.

A total of 1547 events survived this cut, 81 of which were discarded having the maximum p_T of the three muons smaller than 0.4 GeV/c, leaving 1466 events for the final analysis.

All three muons arising from B decay are expected to have an average p_T larger than that of the background. Using this fact, it is found that a good background rejection may be achieved using the variable $p_{T_{\text{tot}}} = p_{T_1} + p_{T_2} + p_{T_3}$.

Figure 2a shows the $p_{T_{\text{tot}}}$ distribution of the selected trimuon events. In figs. 2b and c the $p_{T_{\text{tot}}}$ distributions are shown for the subsamples obtained by requiring $E_{\text{miss}} > 30$ GeV and $E_{\text{miss}} > 50$ GeV, respectively.

The background in the trimuon sample is mainly due to the association of a $\mu^+\mu^-$ pair from Drell-Yan or from $D\bar{D}$ decay with a third ‘non-prompt’ muon coming from π and K decay. It is interesting to note that the background due to the superposition of two different interactions or to the coincidence of an interaction with a beam halo muon is automatically excluded by the calorimetric measurement, since these events would exhibit a total energy much larger than that of the beam. To reproduce the background a trimuon ‘pseudo-event’ sample was constructed by combining measured $\mu^+\mu^-$ events with the measured ‘non-prompt’ single-muon yield. In order to determine experimentally the ‘non-prompt’ muon-momentum distribution, measurements were performed with a single-muon trigger at different dump densities, $\varrho = 1, 2/3, 1/2$ ($\varrho = 1$ standard calorimeter configuration corresponding to ≈ 10.6 g/cm³), and extrapolated to $1/\varrho = 0$. The energy of the neutrino associated with a ‘non-prompt’ muon was computed as coming from π and K decay and combined with the experimental missing-energy distribution from the dimuon sample. The sample of the trimuon background events thus obtained was normalized to the 1466 events of the final data sample.

The expected number of background events may be calculated by combining the observed dimuon rate with the non-prompt rate normalized to the number of interacting pions; thus 1380 ± 250 expected background events are obtained, in excellent agreement with the 1466 selected trimuons.

It should be noted that all the quantities entering into the background estimate used experimental data, the only uncertainty arising from the ratio of K/ π in hadronic showers. This ratio was varied in the interval 0.1–0.2 in the Monte Carlo computations. This uncertainty is taken into account in the evaluation of the error in the background.

In Figs. 2 the $p_{T_{\text{tot}}}$ distributions of the background events are compared with experimental data. Without a missing-energy cut, the background estimate represents well the data over the whole $p_{T_{\text{tot}}}$ range, while for $E_{\text{miss}} > 50$ GeV an excess of events with respect to the background is present at large $p_{T_{\text{tot}}}$ ($\gtrsim 3$ GeV) where the effect from $B\bar{B}$ decay is expected.

A small excess is also present for $p_{T_{\text{tot}}} \lesssim 2.5$ GeV/c and $E_{\text{miss}} > 50$ GeV. This effect can be explained as being due to the production of four charmed particles, a process previously observed in emulsion [7]. The analysis of this process is in progress but its contribution to the $B\bar{B}$ signal is thought to be negligible, assuming that its p_T distribution is similar to that of charm-pair production.

For $p_{T_{\text{tot}}} > 3.2$ GeV/c and $E_{\text{miss}} > 50$ (30) GeV, we obtain 13 (23) events against $1.4^{+1.0}_{-0.7}$ (8.5 ± 4) estimated background events.

The systematic error in the background estimate takes into account the following:

- i) the π/K uncertainty within the quoted limits,
- ii) the uncertainty of non-prompt p_T distribution,
- iii) the possible four-charm contribution.

For the study of the x_F distribution of the $B\bar{B}$ and for the total cross-section determination, we have used the 13 events surviving the cuts: $p_{T_{\text{tot}}} > 3.2 \text{ GeV}/c$, $E_{\text{miss}} > 50 \text{ GeV}$. The acceptance for $B\bar{B}$ giving rise to three muons surviving the above cuts is shown in fig. 3 as a function of x_F .

The relevant kinematic parameters for these 13 events are shown in table 1. It can be seen from table 1 that the energy distributions of the most energetic muon in the selected sample ($E_{\text{miss}} > 50 \text{ GeV}$, $p_{T_{\text{tot}}} > 3.2 \text{ GeV}/c$) does not show any charge asymmetry within the large statistical uncertainty.

Figure 4 shows the distribution of the total leptonic energy ($E_{\text{lept}} = E_{\text{miss}} + \sum E_\mu$) for the signal and the results of a Monte Carlo calculation assuming for the beauty particles an uncorrelated production mechanism with an x_F , p_T distribution:

$$d\sigma/dx_F dp_T^2 \propto (1 - |x_F|)^\alpha \times \exp(-0.9 p_T^2) \quad . \quad (1)$$

The best agreement is obtained for $\alpha \simeq 2.5$. Although the poor sensitivity does not permit an accurate determination of α , pure ‘central’ production with $\alpha = 6$ (as observed in proton-proton charm production [8]) is unlikely.

Assuming that the distribution (1) is valid over the whole x_F range, the acceptances for trimuon events from $B\bar{B}$ decay are $\epsilon = 0.69 \times 10^{-2}$, 0.53×10^{-2} , 0.65×10^{-2} for $\alpha = 2.5$, 4.5, and 0.5, respectively.

The value corresponding to $\alpha = 2.5$ is used in the cross-section calculation. The following branching ratios have been used:

$$\begin{aligned} \text{BR}(B \rightarrow \mu + X) &= 13\% \\ \text{BR}(D \rightarrow \mu + X) &= 11\% \\ \text{BR}(B \rightarrow D) &= 100\% \quad . \end{aligned}$$

The absolute normalization has been determined using a sample of reconstructed ψ events and a value of

$$\sigma_{\pi U}(\psi) \text{BR}(\psi \rightarrow 2\mu) = 1.95 \pm 0.35 \mu\text{b}$$

at 320 GeV obtained by extrapolating the experimental value on a W target at 300 GeV [9].

Under these hypotheses, we obtain

$$\begin{aligned} \sigma_{B\bar{B}} &= 4.5 \pm 1.4 \pm 1.4 \text{ nb per nucleon} && \text{assuming } A^1 \text{ dependence} \\ \sigma_{B\bar{B}} &= 17.6 \pm 5.5 \pm 5.5 \text{ nb per nucleon} && \text{assuming } A^{0.75} \text{ dependence} \quad . \end{aligned}$$

The systematic error takes into account the uncertainty in the absolute normalization and in the acceptance; the uncertainties resulting from the B and D semi-leptonic branching ratios and from the $B\bar{B}$ production mechanism are not included.

We have also observed an excess of events over the background in the $\mu^+\mu^+$ and $\mu^-\mu^-$ events consistent with these results. The analysis of this sample is in progress.

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Table 1

E_{miss} , p_T 's and E_μ 's for each of the 13 trimuon events surviving the cuts discussed in the text; the sign refers to the muon charge

Event No.	E_{miss} (GeV)	E_{μ_1} (GeV)	p_{T1} (GeV/c)	E_{μ_2} (GeV)	p_{T2} (GeV/c)	E_{μ_3} (GeV)	p_{T3} (GeV/c)
1	57	-51	2.0	-38	1.0	+27	0.2
2	75	+18	0.8	-35	1.2	+45	1.3
3	51	+69	1.8	+17	0.9	-25	1.4
4	100	+19	1.0	+21	1.2	-74	2.0
5	63	-39	1.9	-31	1.2	+23	1.8
6	102	+45	0.5	-33	1.1	-40	2.2
7	79	-26	1.1	+24	1.0	-60	1.9
8	55	-36	0.8	+26	2.1	-31	0.7
9	137	-19	0.6	+36	1.3	+33	1.4
10	50	+41	1.4	-59	1.4	-30	1.3
11	51	-37	1.1	+22	0.8	+68	2.1
12	93	+48	1.3	-20	0.5	-38	1.8
13	54	-21	0.3	-20	0.2	+37	2.8

Figure captions

Fig. 1 General layout of the experiment.

Fig. 2 $p_{T_{\text{tot}}}$ distributions for the accepted trimuon events;

a) without a cut in E_{miss} ;

b) $E_{\text{miss}} > 30$ GeV;

c) $E_{\text{miss}} > 50$ GeV.

The solid line represents the background estimate. The dashed line is the Monte Carlo prediction for $B\bar{B}$ produced according to expression (1) with $\alpha = 2.5$. The Monte Carlo events are normalized to the experimental data at $E_{\text{miss}} > 50$, $p_{T_{\text{tot}}} > 3.2$ GeV/c.

Fig. 3 x_F acceptance for the fast and for the slow beauty particle in the trimuon events surviving the cuts discussed in the text.

Fig. 4 E_{lept} distribution of the events surviving the cuts discussed in the text compared with Monte Carlo predictions, for different values of α . The cut at 240 GeV corresponds to the cut $E_{\text{cal}} > 80$ GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4