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OBSERVATION OF WRONG-SIGN TRI-MUON EVENTS
IN 250 GeV MUON-NUCLEON INTERACTIONS

The European Muon Collaboration

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Abstract

Two trimuon events of the type $\mu^+ N \rightarrow \mu^+ \mu^+ \mu^+ X$ and one $\mu^+ N \rightarrow \mu^+ \mu^- \mu^- X$ have been observed in 250 GeV μ^+ -iron interactions. The expected rate from the decay of hadrons (charm, π , K) is about one event. Other processes that may contribute are both beauty production and charm production with D^0 - $\bar{D}^0$ mixing. The data give upper limits of 12×10^{-36} cm² for the cross-section of beauty pair production by muons, and 20% for $D^0 \leftrightarrow \bar{D}^0$ transitions due to mixing, both at 90% confidence level.

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This paper reports the observation of two events of the type $\mu^+N \rightarrow \mu^+\mu^+\mu^+X$ and one of the type $\mu^+N \rightarrow \mu^+\mu^-\mu^-X$ which are called 'wrong-sign' as the summed outgoing trimuon charge is different to that of the beam. This is in contrast to the more common processes such as electromagnetic Bethe-Heitler production, vector meson decay, and normal charm decay events, in which these charges balance.

Wrong-sign final states are expected from beauty pair ($\overline{B}B$) production in which the observed muons are produced in the semi-leptonic decays of one $B(\overline{B})$ and a charm particle in the decay chain of the $\overline{B}(B)$. Many predictions have been made for the $\overline{B}B$ production cross-section for lepton and photon beams [1-7]. Previous evidence for $\overline{B}B$ production has come from storage ring experiments at CESR [8-10].

A second process that can produce wrong-sign events is one in which D^+D^0 , D^0D^- , $D^0\overline{D}^0$ production occurs followed by a $D^0 \leftrightarrow \overline{D}^0$ transition due to mixing. If both D's then decay semi-leptonically a wrong-sign final state is produced [11-14]. There has been no previous observation of such mixing, but upper limits have been given [15, 16].

These events could also be produced in normal deep inelastic scattering in which two π 's or K's of the same sign produced in the hadron shower decay to muons, or in charm production where one charm particle and a same sign π or K decay to muons.

The three wrong-sign trimuon events were obtained during a study of multimuon production in μ^+ -iron interactions made using the EMC forward spectrometer in the muon beam at the CERN SPS. The apparatus is shown in fig. 1 and described in detail elsewhere [17]. The μ^+ beam had a mean energy of 250 GeV with a momentum bite of 8% FWHM. Each incident muon was measured in momentum ($\pm 0.3\%$), position and angle. The target was a 3.75m long Sampling Total Absorption Calorimeter (STAC), consisting of 36 iron/scintillator sandwich modules. Hadrons produced in an interaction generated a shower that was absorbed in the STAC, thereby giving a measurement of the total energy of the hadrons, with a resolution of $\sigma = 0.41 E^{0.6}$ where E is in GeV. The upstream 2.8m of the STAC was defined as the fiducial region of the target. The integrated luminosity was $3.5 \times 10^{38} \text{ cm}^{-2}$. The outgoing muons were measured both in angle and momentum in the downstream spectrometer and required to pass through

the equivalent of 2.9m of iron which constituted the muon filter of the experiment. The resolution of the measurement of outgoing tracks was dominated by energy loss uncertainties and multiple scattering in the STAC. The trackfinding analysis and event reconstruction were the same as those used for other multimMuon studies [18].

In the sample of fully reconstructed trimuon events 12 $\mu^+ \mu^+ \mu^+$ and 3 $\mu^+ \mu^- \mu^-$ were found. Each event was individually examined and required to satisfy the following conditions:

- 1) To avoid contamination from two separate deep inelastic events it was required that there should be no extra beam track within 10 nsec of the detected event nor more than one observed shower in the STAC.
- 2) To avoid contamination from random halo tracks the measured time of each of the three outgoing muons was required to be within 4 nsec of that of the incident muon. It was also required that there be no extra track segments been found by the reconstruction programme in the forward spectrometer.
- 3) To reduce the effects of hadron punch-through, it was required that the energy in the three elements upstream of the point where any muon left the STAC be no larger than that expected from minimum ionising muons traversing those elements.

The effect of these cuts in removing good events was estimated by applying the same criteria to the sample of 'correct-sign' trimuon events. A correction of 30% was measured and included in the calculated acceptance for wrong-sign events.

Two $\mu^+ \mu^+ \mu^+$ and one $\mu^+ \mu^- \mu^-$ events satisfied all of these criteria. The parameters of the events are given in Table 1. The reconstructed tracks for event A are shown in fig. 1.

These wrong-sign trimuon events cannot be produced via vector meson production or normal decay of charm hadrons without the additional decay of a π or K in the same event. The expected number of events from the decay of a charm particle plus a π or K has been calculated to be 0.6 events using a model that gives a good description of the observed dimuon and trimuon data attributed to charm decay [18]. The expected number of events from double π or K decay has been calculated to be 0.3 events. As these estimates of conventional processes give a number of events comparable with that observed it is possible that all events come from these sources. However all outgoing tracks of event A have such large transverse momenta that it is unlikely to be an example of one of these processes.

The three observed events may be interpreted as beauty meson production and decay as follows:

To calculate the acceptance for such events a Monte Carlo simulation of $B\bar{B}$ production based on the photon-gluon fusion model has been used. The parameterisations used for the gluon distribution and the fragmentation functions were those used for the simulation of charm production [18]. The acceptance was calculated to be 11% for $\mu^+ \mu^+ \mu^+$ events and 6% for $\mu^+ \mu^- \mu^-$ events, with an estimated uncertainty of a factor 1.4 as the acceptance calculation is model dependent. The three observed events (assuming one background event) correspond to

a cross section of $(5 \pm 5) \times 10^{-36} \text{ cm}^2$ for $B\bar{B}$ production assuming that the mean semi-leptonic branching ratios for both charm and B decay are 10%, in agreement with published data [8,9,19]. Expressing these results as an upper limit for $B\bar{B}$ production yields the result

$$\sigma(\mu N \rightarrow \mu B\bar{B}X) < 12 \times 10^{-36} \text{ cm}^2 \text{ (90\% confidence level) at 250 GeV.}$$

Assuming the model gives the correct dependence of the cross-section with the virtual photon variables, the events correspond to a photoproduction cross-section of about $2 \times 10^{-33} \text{ cm}^2$ at 200 GeV. These results have an additional uncertainty of about a factor 2 arising from the quoted errors on the branching ratios and the unknown proportion of charged and neutral D's in the decay chain. This upper limit is similar to that obtained from a study of dimuon events by A.R. Clark et al. [20].

Predictions for $B\bar{B}$ production in photon and lepton beams have been made using empirical formulae [1], vector dominance [2, 3], and photon-gluon fusion models [4, 7]. The photon-gluon fusion model predictions of Leveille and Weiller [6] of $3 \times 10^{-36} \text{ cm}^2$ and of Barger, Keung and Phillips [7] of $5 \times 10^{-36} \text{ cm}^2$ for the muoproduction cross-section and the predictions of Ellis et al. [1] of $1-10 \times 10^{-33} \text{ cm}^2$ for the photoproduction cross-section, are in agreement with these data.

The events may also be interpreted as $D\bar{D}$ production as follows:

$$\begin{array}{l} \mu^+ N \rightarrow \mu^+ (D^+ \text{ or } D^0) \bar{D}^0 X \\ \quad \downarrow \qquad \qquad \downarrow \\ \quad \quad \quad p^0 \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^+ \nu + \text{hadrons} \\ \downarrow \\ \mu^+ \nu + \text{hadrons} \end{array}$$

and

$$\begin{array}{l} \mu^+ N \rightarrow \mu^+ (D^- \text{ or } \bar{D}^0) D^0 X \\ \quad \downarrow \qquad \qquad \downarrow \\ \quad \quad \quad \bar{D}^0 \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^- \bar{\nu} + \text{hadrons} \\ \downarrow \\ \mu^- \bar{\nu} + \text{hadrons} \end{array}$$

The probability of $D^0 \leftrightarrow \bar{D}^0$ transitions due to mixing is expected to be small, about 10^{-3} in the standard GIM model [21], but other models have been proposed in which the mixing is larger [11, 12]. An upper limit on this probability can be obtained by comparing the observed rates of production of correct-sign and wrong-sign trimuons from charm production. For this comparison, events were selected as in reference [18] such that the effective mass of the two lower momentum μ 's was in the range $1.0 < M_{\mu\mu} < 2.5$ GeV. One of the wrong-sign events (event B) and 83 correct-sign events were in this region. The assumptions were made that half the charm decays were from D mesons, the rest being from other charmed mesons and baryons [22], and that the different charged states $D^+ \bar{D}^0$, $D^+ D^-$, $D^0 \bar{D}^0$, $D^0 D^-$ were produced with equal probability. Using the measured semi-leptonic branching ratios [19], the observed event corresponds to an upper limit of the transition probability of 0.20 (90% confidence level). This is similar to previous limits [15, 16].

To summarise, 'wrong-sign' trimuon events of the type $\mu^+ \mu^+ \mu^+ X$ and $\mu^+ \mu^- \mu^- X$ have been observed in 250 GeV $\mu^+ N$ interactions. Two of the three observed events could originate from conventional decays (charm, K, π) for which the estimated rate is 1 event. However, the data allow an estimate of 5×10^{-36} cm² corresponding to an upper limit of 12×10^{-36} cm² (at 90% confidence level) to be made for the $B\bar{B}$ production cross-section, consistent with photon-gluon fusion model predictions. They also allow an upper limit of 20% (90% c.l.) to be put on $D^0 \leftrightarrow \bar{D}^0$ transitions due to mixing.

TABLE 1

EVENT	TRACK	ENERGY [GeV]	P _x [GeV]	P _y [GeV]	P _z [GeV]
A	Beam		245.9	0.05	0.15
	μ^+		64.9	-1.42	-0.42
	μ^+		33.9	-2.19	0.42
	μ^+		17.1	2.24	0.36
	Hadronic	75 $\pm$ 6			
	Missing	55 $\pm$ 7			
B	Beam		269.0	0.05	0.08
	μ^+		50.7	-0.12	0.35
	μ^+		17.6	0.05	-0.35
	μ^+		14.4	0.58	0.45
	Hadronic	161 $\pm$ 9			
	Missing	25 $\pm$ 10			
C	Beam		253.9	0.03	-0.05
	μ^+		37.2	-0.16	-0.23
	μ^-		44.5	0.25	0.03
	μ^-		29.5	0.60	-0.27
	Hadronic	104 $\pm$ 7			
	Missing	38 $\pm$ 8			

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FIGURE CAPTIONS

Fig. 1 Plan view of the apparatus showing the reconstructed tracks of event A. BHA, BHB are beam hodoscopes, V1-3 are veto hodoscopes, H1-4 are trigger hodoscopes, H5 is a beam monitor hodoscope, W1-7 are arrays of drift chambers and PO-3 are arrays of proportional chambers. The x, y axes are those referred to in Table 1. The z axis is vertically upwards.

PLAN VIEW

Fig. 1