DIRECT OBSERVATION OF THE DECAY OF BEAUTY PARTICLES INTO CHARM PARTICLES

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ABSTRACT

The associated production of a pair of beauty particles B^- and $\bar{B}^0$ by a 350 GeV π^- interaction has been observed in an emulsion target inserted in an array of silicon microstrip detectors. Both beauty particles decay into charm particles, both of which are also observed to decay in the emulsion. Two negative muons were identified and their momenta measured in a large muon spectrometer. One muon has a p_T of 1.9 GeV/c and is associated with a beauty particle decay. The other, with a p_T of 0.45 GeV/c is associated with a charm particle decay. The flight times of the two beauty particles are respectively $(0.8 \pm 0.1) \times 10^{-13}$ s and $(5.4 \pm 1.1) \times 10^{-13}$ s. Alternative interpretations of this event have negligible probability.

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The experiment described below was designed to observe directly the decay of beauty particles [1] and to measure their lifetimes. Since the discovery of the τ [2], several observations of beauty particles have been reported [3], some permitting an indirect measurement of their mean lifetime. Nevertheless, no beauty particle decay had been observed directly until now. Previous experiments [4] have set very low limits on the production cross-section of beauty particles at Super Proton Synchrotron (SPS) energies.

DESCRIPTION OF THE EXPERIMENT

The present experiment, WA75 [5], used a combination of electronic and emulsion techniques. The characteristic signature of a beauty event in an emulsion stack was chosen to be the presence of at least three, or possibly four decay vertices, resulting from the decay of the two beauty particles and one or two from the subsequent decay of charm particles. The extremely small setting error of 0.5μ and the high grain density for minimum ionizing tracks (20 grains per 100μ) provided by the emulsion technique leads to a sensitivity to lifetimes as short as 10^{-14} s and an excellent resolution of secondary tracks at the primary vertex. In these circumstances, it can be shown [5] that the background due to secondary and tertiary interactions simulating such a decay chain is very small.

A total of 80 litres of emulsion was exposed in the form of stacks composed of pellicles which were oriented either in directions perpendicular or parallel with respect to the beam. Perpendicular stacks were 18.5 mm thick along the beam. They were exposed to 3000 tracks/mm^2 . This density provides a high sensitivity in terms of cross-section. Parallel stacks, which provide the best sensitivity in terms of lifetime, were 40 mm thick along the beam and were exposed to 1500 tracks/mm^2 . Emulsion stacks were prepared from fresh Fuji and Ilford gels and poured at CERN. The stacks were mounted on a moveable stage, the position of which was measured with a precision of 5μ . The stage under the control of a micro-processor linked to a PDP 11/44 computer moved with a speed proportional to the instantaneous beam intensity. Hence a uniform irradiation of the emulsion was obtained.

As the production cross-section of beauty particles was expected to be small, a large number of interactions was recorded in the emulsion, 3×10^8 . The number of interactions to be studied could however be reduced drastically by requiring the presence of a high p_T muon, characteristic of the semi-leptonic decay of a beauty particle, in a magnetic spectrometer downstream of a 2 m iron-tungsten dump.

The spectrometer (Fig. 1) had an acceptance of ± 170 mrad in the horizontal plane and ± 60 mrad in the vertical plane, and the bending power of the magnet was 3 Tm. A set of 12 planes of 1 mm pitch multiwire proportional chambers (MWPC) and 9 planes of drift chambers with a 200μ precision in front of the magnet gave the position and direction of the muon at the entrance of the spectrometer. A further set of 12 planes of 2 mm pitch MWPC's behind the magnet determined the muon deflection. The resolution of the spectrometer was found to be $\Delta p/p = 0.6 \times 10^{-3} p$ (GeV/c). The error in transverse momentum Δp_T was ~ 0.075 GeV/c.

The on-line trigger selected 1.5×10^6 of the interactions by requiring that at least one muon be detected by large scintillator hodoscopes in the muon spectrometer. These hodoscopes were put in coincidence with a beam counter and with an interaction multiplicity counter placed just downstream of the emulsion. A small counter centered on the beam line downstream of the dump vetoed penetrating particles at small angles to the beam. The final selection was made off-line by requiring the presence of at least one muon with $p_T > 1$ GeV/c, thus reducing the number of events to be studied to 1×10^4 (Fig. 2).

In order to restrict the scanning volume, a beam hodoscope comprising 6 planes of silicon microstrip detectors with 50μ pitch was placed in front of the emulsion, (Fig. 1). The beam hodoscope precision was measured to be 15μ in the two directions perpendicular to the beam [6].

The vertex detector (Fig. 1) immediately downstream of the emulsion contained 10 planes of silicon microstrips with pitches of 50, 100 and 200μ oriented along 4 directions. The silicon detectors were followed by 16 planes of 1 mm pitch multiwire proportional chambers (MWPC), which provided a larger angular coverage than that of the silicon detectors. The beam hodoscope, the emulsion stage mover and the vertex detector were

aligned on a granite table surfaced to a precision of $\pm 4\mu$ and the whole assembly was temperature-controlled to $\pm 0.5^\circ\text{C}$. The purpose of the vertex detector was two-fold: first, together with the beam hodoscope, it gave the position of the interaction vertex in emulsion by the reconstruction of secondary tracks. Secondly, it provided the topology of the events, hence permitting a match with the tracks found in the emulsion, and also with the muon tracks found in the spectrometer. This establishes the temporal correlation with the primary interaction of tracks from neutral particles decaying in emulsion.

The experiment was installed in a 350 GeV π^- beam provided by the CERN Super Proton Synchrotron (SPS). The beam had a 0.5% resolution in momentum and its size ($\phi \sim 1\text{mm}$) was continuously monitored by the silicon detectors.

ANALYSIS

The off-line analysis started with the pattern recognition in the muon spectrometer and the reconstruction of the muon tracks, making corrections for the energy loss inside the dump. To reduce the error due to multiple scattering, the algorithm described in ref [7] was used assuming the production vertex to be at the mid-point of the emulsion stack along the beam axis. Muon tracks reconstructed in the spectrometer were required to point to the target to within 4σ (where σ is the most probable multiple scattering error). The errors on the reconstructed track angle in radians were $0.075/p$ (GeV/c) and $0.18/p$ (GeV/c) respectively for muons traversing the iron or tungsten part of the dump.

The distribution of the difference in angle between the muon track in the spectrometer and the nearest track in the emulsion had a sharp peak at small values, the width of which was due to multiple scattering in the dump. Tracks for which the angular difference was less than 4 standard deviations were said to be associated and this occurred for 75% of the events found in emulsion. (For these, in 80% of cases, the muon track was also reconstructed in space in the vertex detector). The associated muon tracks were found to originate from the primary vertex in 90% of the cases, and were due either to direct muon production or to π 's and K's decaying

into muons in flight. The small transverse momentum of the muon relative to the π direction made the two trajectories indistinguishable. For K's, this was not always true, and it is estimated that most of the failed associations were due to $K \rightarrow \mu\nu$ decays in flight. In about 10% of the cases the muon track was not present at the primary vertex and these events were subjected to further analysis.

The interactions to be searched for in the emulsion were selected by requiring that at least one muon with $p_T \geq 1$ GeV/c with respect to the beam direction be present. The position of the vertex in the emulsion was predicted with typical errors of 20μ in transverse directions and 500μ along the beam. The relative position of the emulsion and the electronic detectors and the location of emulsion pellicles within a stack were determined by low density exposures, small size beam spots, narrow X-ray lines and grid printing. Including errors from all sources, a final overall precision of about 70μ transverse to the beam was achieved, as determined by calibration with well identified events in the emulsion. The scanning volume was then restricted to typically a cylinder of radius 200μ and a length along the beam of about 3 mm. Despite the high flux of primaries, the search volume was sufficiently small to contain usually only one interaction, thus simplifying the identification of the primary vertex.

Minimum ionizing tracks from the primary vertex were followed in the forward direction for three millimetres to search for decays of charged particles. A cylinder of radius 150μ and at least 3 mm long was scanned for neutral decay topologies.

A number of cases of associated production of charmed particles were observed and recently an event with the characteristic features expected from beauty particle production has been found. It is described below.

DESCRIPTION OF THE EVENT

The event (Fig. 3) was found in an emulsion pellicle exposed parallel to the beam. Using the vertex detector, 15 tracks were reconstructed in space from respectively 20 and 21 track projections in two orthogonal planes. The position of the primary vertex in the emulsion was defined

using 11 of these space tracks. The remaining 4 tracks are discussed later. Two negative muons were detected in the magnetic spectrometer and their total momenta and momenta transverse to the beam direction were respectively $p = 27.7 \text{ GeV/c}$, $p_T = 2.1 \text{ GeV/c}$ and $p = 11.5 \text{ GeV/c}$, $p_T = 0.40 \text{ GeV/c}$. The extrapolated direction of the higher energy muon had excellent association with a space track in the vertex detector, whilst the other muon track could be matched to a space track in the vertex detector within 2.5 standard deviations.

The primary star, comprising three evaporation tracks and six minimum ionization tracks, was found 33 mm from the exit edge of the pellicle and well within the searched volume. The directions of the six minimum ionizing particles were determined and their tracks were followed through the emulsion. One underwent a nuclear interaction which produced no charged particles detected by the vertex detector, four were well associated with space tracks. The sixth was observed to have a 68 mr change of direction at a distance of 437 μm from the parent star and subsequently it showed a very good association with that space track in the vertex detector identified with the higher energy muon.

The search downstream from the primary star revealed two stars which exhibited topologies expected for the decay of neutral particles. The four prong vertex 2 was found 775 μm downstream of the change of direction and 1215 μm downstream of the primary vertex. The directions of the particles were measured and three of them were matched with those of corresponding tracks in the vertex detector. The fourth particle gave rise to a nuclear interaction after traversing 18 mm of emulsion. In addition to nine evaporation particles, this interaction produced three minimum ionizing particles and these were also registered in the vertex detector. However, these tracks had been rejected by the vertex reconstruction program because they did not point to the primary vertex. The two prong vertex 3 was found 4.43 mm from the primary vertex. One of the two tracks was directly associated with a track in the vertex detector, the other underwent a change of direction of 39 mr after a path length of 8.4 mm. After the change of direction this track was also well associated with that vertex detector track which matched most closely the lower energy muon in the spectrometer. Multiple scattering measurements performed on the

available track lengths indicated energy values in excess of 5 GeV for both particles. This fact together with the large opening angle made interpretation as an electron pair impossible.

All the directions of particles in emulsion were measured with errors of about 2-3 mradians. Since all the particles of interest had small dip angles (< 90 mradians) the effect of distortion was very small but nevertheless allowance was made for it. The emulsion vertex detector and spectrometer measurements are presented in Table 1 together with the associations made.

DISCUSSION AND CONCLUSION

The obvious interpretation of the event (Fig. 3) is as the production of a $B^- \bar{B}^0$ pair by the primary 350 GeV/c π^- meson interaction. The B^- decays at vertex 1 into a negative muon and a neutral charm particle, presumably a D^0 meson, which itself decays at vertex 2 into four charged particles. The $\bar{B}^0$ decays at vertex 3 into a positive hadron and a negatively charged charmed particle, presumably a D^- meson which decays into a negative muon at vertex 4.

The excellent matching of the tracks from the decays of the neutral particles with those seen in the vertex detector establishes without doubt the overall correlation of the various features of the event observed in the emulsion. This, together with the presence of a high p_T muon, renders alternative interpretations of the event extremely improbable. The most likely of the alternative explanations is that vertex 1 is due to an interaction of a pion from the primary, producing just one wide angled charged pion which subsequently decays before reaching the dump. Vertices 2 and 3 are then assumed to be due to the decays of neutral charmed mesons and vertex 4 to some other nuclear interaction. The probability of such a topological sequence is estimated to be $< 10^{-5}$ at the present stage of the analysis. The presence of a second negative muon, and the kinematical constraints to be discussed below were not taken into account in this background calculation, because they were not part of the selection criteria. They would obviously tend to reduce the estimated background.

The mass of the supposed B^- must be high as it decays into a secondary with a relative p_T of 1.9 GeV/c. On the other hand, the second μ^- has a p_T of 0.45 GeV/c with respect to its parent's line of flight, providing good evidence that it comes from a charm particle decay. As shown below, the D^- has a momentum of ~ 50 GeV/c, and consequently the relative transverse momentum of the D^- at the $\bar{B}^0$ decay vertex is 1.2 GeV/c. This supports the evidence that the supposed $\bar{B}^0$ is also a heavy particle.

Since, apart from muons, the particles identities and energies are unknown, the kinematic analysis is far from complete. Nevertheless, two different methods have been used to evaluate the proper times of flight of the beauty particles. The impact parameter method [8] was used to estimate the beauty flight times t . In the approximation that the decay products have $\beta \sim 1$ in both the centre of mass and laboratory systems, the γ factor and emission angle θ of a decay product for an isotropic emission are related by $\gamma \sim 1/\langle\theta\rangle$ and $ct = L \langle\theta\rangle$ where L is the decay path. For the B^- , $\gamma \sim 21$ (i.e. $p \sim 120$ GeV/c) and t is $.7 \times 10^{-13}$ s. (The same method applied to the D^0 gives $\gamma \sim 33$ and $t \sim 0.8 \times 10^{-13}$ s.) The momenta of the observed B^- decay products then sum up to 90 GeV/c, consistent with the 120 GeV/c deduced above when allowance is made for a missing neutrino and other neutrals. The same method applied to the $\bar{B}^0$ gives $\gamma \sim 50$ (i.e. $p \sim 280$ GeV/c but with a large error) and $t \sim 3 \times 10^{-13}$ s. For the D^- one finds $\gamma \sim 26$ and $t \sim 1.1 \times 10^{-12}$ s.

The second method assumes plausible decay schemes [9]. The decay kinematics were computed in the laboratory system by varying the decaying particle energies from 10 to 250 GeV and those of the decay products from 1 GeV to the maximum allowed by the emission angle and assigned mass. The method has been applied to the four vertices of the event. The precise knowledge of the momentum of the muon and the emission angle of the neutral charmed particle V4 decaying at vertex 2 constrain the B^- energy to lie between 70 and 120 GeV. Moreover, the phase space giving the observed configuration may be evaluated as a function of the energy of the B^- particle. The resultant weighted value of the B^- energy is (98^{+12}_{-15}) GeV and the corresponding flight time is $(0.8 \pm 0.1) \times 10^{-13}$ s. The application of the method to V4 decaying at vertex 3 gives an energy of 60 ± 20 GeV for

the neutral charmed particle, compatible with the values obtained analysing the B^- vertex. The hypothesis that the V2 decay at vertex 3 is that of a D^0 coming from the B^- decay may be ruled out because it is impossible to satisfy the beauty particle decay kinematics with a charmed particle emitted in this direction.

The knowledge of the line of flight from the primary vertex to vertex 3 and of the line of flight of the D^- , together with the positive hadron direction loosely constrains the energy of the $\bar{B}^0$ to lie between 30 and 210 GeV. If the positive particle has a mass higher than that of a pion this upper limit will be somewhat reduced. Phase space calculations similar to those performed for the B^- decay indicate that the $\bar{B}^0$ energy is (160^{+30}_{-40}) GeV and the corresponding flight time is $(5^{+2}_{-1}) \times 10^{-13}$ s. The D^- energy is 40 ± 15 GeV.

The weighted mean flight time of the B^- and $\bar{B}^0$ is

$$t_B = (3^{+2}_{-1}) \times 10^{-13} \text{ s}.$$

Much longer lifetimes could have been detected since the primary vertex was very close to the upstream edge of the emulsion stack.

About 10% of the available material has now been analysed. Assuming an A dependence of the cross-section, the event found indicates a beauty particle production cross-section in the region of 10 nb.

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This letter is dedicated to the memory of Brian Duff
whose untimely death occurred before the completion of the experiment.

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FIGURE CAPTIONS

Fig. 1: Experimental set-up. The overall length of the experiment along the beam is 13.5 m.

Fig. 2: Experimental p_T distribution for all muon tracks reconstructed in the spectrometer and calculated p_T distribution for the signal from the Monte Carlo.

Fig. 3: Sketch of the $B-\bar{B}^0$ event.

FIG. 1

FIG. 2

FIG. 3

Emulsion azimuth (α) and dip (δ) angles in mradians										Vertex detect.		Spectro.	
α	δ	α	δ	α	δ	α	δ	α	δ	α	δ	α	δ
π^-													
350 GeV/c													
μ^-													
11.5 GeV/c													
0.40 GeV/c													
27.5 GeV/c													
2.12 GeV/c													
Rej.													
Rej.													
Rej.													
X													
NUCL. INTER. (2.4 mm)													
D ⁺ (775 μ m)													
B ⁻ (437 μ m)													
NUCL. INTER. (18 mm)													
D ⁺ (12.2 mm)													
26.6 mm													
-102 +106													
+76 +147													
+50 +34													
(-94) (-189)													
+65 +161													
+49 +33													
-33 +38													
-36 -20													
-35 +68													
-52 -55													
+1 +16													
-54													
+2 +9													
(31.5 mm)													
B ⁺ (4.43 mm)													
-1 +23													
+24 -7													
(8.40 mm)													
μ^- (18 mm)													
(27.2 mm)													
+6 -14													
+7 -15													
+23 -9													
+51 -22													
(+20) (0)													
+48 -20													
(29.3 mm)													
+20 0													
(31.5 mm)													
+8 -6													
+2 +9													
(31.5 mm)													
-30 +83													
-46 +85													

Table 1