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MUON-ELECTRON EVENTS IN HIGH-ENERGY PROTON-PROTON COLLISIONS

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ABSTRACT

We have searched for events in proton-proton collisions, at the CERN Intersecting Storage Rings, which contain a muon and an electron of opposite sign. Such events cannot come from the decay of a single vector meson or from the Drell-Yan process, but can come from the semileptonic decays of a pair of charmed mesons. We find a signal of 32 ± 16 events. Assuming that the signal is caused by charmed meson pairs, and using a model for the p_T and p_L distribution of such pairs, we estimate the total inclusive charm production cross-section in proton-proton collisions to be $(70 \pm 36) \mu\text{b}$.

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We report here on an experiment to detect, in proton-proton collisions, events containing both a muon and an electron of opposite sign. Such events cannot result from the decay of any single known particle. They can, however, result from the weak decays of a pair of particles with new quantum numbers, such as the charmed particles which have been observed in e^+e^- [1] and photo-production [2] experiments but not yet with strongly interacting beams. Most background processes (for example $\pi \rightarrow \mu\nu$ decay and the Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$) produce equal numbers of same-sign and opposite-sign μe combinations; hence the experiment was designed to search for an excess of μ^+e^- over μ^+e^+ events.

The experiment was performed at the CERN Intersecting Storage Rings (ISR). Data were taken for an integrated luminosity of $1.5 \times 10^{37} \text{ cm}^{-2}$ at centre-of-mass energy $\sqrt{s} = 53 \text{ GeV}$ and $0.5 \times 10^{37} \text{ cm}^{-2}$ at $\sqrt{s} = 63 \text{ GeV}$. The apparatus, shown in fig. 1, consisted of two electron spectrometers located one on each side of the ISR interaction region, and a muon spectrometer located between the two electron spectrometers and looking down on the plane of the ISR.

As a particle moved into one of the electron spectrometers, it encountered the thin wall of the ISR vacuum chamber (0.3 mm of titanium); two planes of drift chambers placed close to the vacuum chamber, a two-layer hodoscope each of 8 counters (A), and five planes of drift chambers completing the front module; a twelve-cell Čerenkov counter (Č) located in the gap of a large-aperture magnet ($\int B d\ell = 0.3 \text{ T}\cdot\text{m}$); four or six planes of drift chambers (depending on the spectrometer); a 22-element hodoscope of vertical counters (E); a 2 cm thick iron plate; a 20-element hodoscope of vertical counters (F); and, finally, an array of 7×20 lead-glass counters, each 14.8 radiation lengths thick and $15 \times 15 \text{ cm}^2$ in cross-section. The solid angle coverage of each spectrometer was 0.5 sr ($55^\circ \leq \theta \leq 125^\circ$ in polar angle and $\Delta\phi = \pm 15^\circ$ in azimuth).

The momentum resolution of each spectrometer was

$$\Delta p/p = [9 + (4.2 p)^2]^{1/2}, \quad (1)$$

where p is in GeV/c, the constant term is the multiple Coulomb scattering contribution, and the p -dependent term comes from the spatial resolution of the chamber. The energy resolution of the lead glass for electrons was

$$\Delta E/E = [0.05^2 + (0.11^2/E)]^{1/2}, \quad (2)$$

where E is in GeV. A detailed description of the electron spectrometers and of their performance is given elsewhere [3].

For trigger purposes, the $\check{C}$, E, F, and lead-glass counter arrays were subdivided into quadrants. In each electron arm, an electron (e) trigger was defined as a coincidence between corresponding elements in the A-hodoscope and signals from matching quadrants of $\check{C}$, E, F, and lead-glass counters. The lead-glass signal was required to exceed a threshold corresponding to 400 MeV. A hadron (H) trigger was similarly defined from A, E, and F signals. The ratio of e to H trigger rates was about 10^{-2} .

It is known from many other experiments [4] that the inclusive e/π ratio is roughly 10^{-4} in our kinematic region. The ratio of 10^{-2} actually observed at the trigger level depends on the lead-glass threshold, and is predominantly due to known sources of electrons such as γ conversion in the vacuum chamber wall, π^0 or η Dalitz decays, and to misidentified hadrons.

In the analysis, a track extending from the source to the lead-glass array was defined to be an e^+ or e^- candidate if it had associated hits in both layers of the A-counters, and in the $\check{C}$, E, and F hodoscopes. Furthermore, it was required that the energy deposited in the lead glass be in, at most, two adjacent blocks, and that there be no other track pointing to these blocks. The lead-glass energy (corrected for the loss in the iron plate) and the track momentum were required to agree within two standard deviations as defined by Eqs. (1) and (2). Both p and E were required to be greater than 600 MeV.

Most of the e candidates originate from the γ and Dalitz sources of e^+e^- pairs. While events with two e candidates were rejected, asymmetric pairs could produce events with a single e candidate track. All available indications of the pair origin of such tracks were used to eliminate this background. Thus it was required that each associated A-counter give a pulse height ≤ 1.35 times minimum ionizing, and that the track be ≥ 2 mm from the edges of these counters. To eliminate conversions in the A-counter, a hit was required in at least one of the

first two chamber planes. In the front drift-chamber module no additional track or isolated chamber hits were allowed within ± 70 mrad of the e candidate. In addition, we rejected events with more than one track in a "hit" $\checkmark$ cell, or when the e track projected to within 5 cm from the top or bottom, or 10 cm from the sides of the lead-glass array.

A pulse-height threshold imposed on the $\checkmark$ counters, reducing the electron efficiency by 68%, increased the $\checkmark$ hadron rejection to 320 ± 40 from a value of 80 without pulse-height cut. To reject hadrons further, the F pulse height was required to be ≥ 1.4 times minimum ionizing. Because of the electromagnetic showers developing in the iron plate, 86% of the electrons passed this cut compared with 20% of the hadrons.

The effect of the cuts on the electron detection efficiency was evaluated from a sample of ~ 1000 J/ψ events [3], for which an electron was detected in each spectrometer arm. While keeping the standard cuts on one electron, the cuts on the other could be varied individually. The electron efficiency was measured to be $16 \pm 3\%$. An independent determination of the efficiency was made in two steps: all losses unrelated to the electron identification were obtained from the ratio of the charged hadron yield measured in our apparatus (H trigger) to the inclusive production cross-section measured by Alper et al. [5]; and a sample of converted gamma-rays was used to evaluate the losses associated with the $\checkmark$, F, and lead-glass cuts. Excellent agreement was obtained. Individual contributions to the efficiency included the A pulse-height (75%), $\checkmark$ trigger efficiency and pulse-height cuts (56%), F (86%), and lead-glass cuts (80%).

The effectiveness of these methods of background reduction was assessed by measuring the inclusive e/π ratio from a comparison of data taken with the e trigger and with the H trigger, analysed with our standard programs, and corrected for both the detection efficiencies and the π /hadron ratio [5]. The data are shown in fig. 2 together with measured and calculated backgrounds. The computed Compton and K_{e3} backgrounds are below 0.5×10^{-4} . The hadron misidentification contribution is also low; it was determined from the observed hadron yield combined with the measured rejection factors of the $\checkmark$ and of the F/lead-glass combination.

The most important background is due to asymmetric Dalitz decays of π^0 and η mesons. It was evaluated with a Monte Carlo calculation which used as input the π^0 production cross-section*) and an η/π^0 ratio [6] of 0.43 measured at c.m. momentum $p_T \approx 2$ GeV/c and scaled to 0.21 at $p_T = 0.5$ GeV/c with the parametrization of Ref. [7]. The η contribution to the background is about $1/4$ to $1/2$ that of the π^0 . After background subtraction the average e/π ratio over the interval $0.5 \leq p_T \leq 2.4$ GeV/c is $(1.3 \pm 0.4) \times 10^{-4}$, consistent with other measurements [4].

The muon spectrometer (fig. 1) had angular acceptances $60^\circ \leq \theta \leq 120^\circ$ and $\Delta\phi = \pm 13^\circ$. Particles emitted from the source passed first a 2.5 cm thick iron shield protecting the ISR beams from the electron spectrometers' fringe field; then a 7 radiation length thick lead plate; a scintillator array B; a first tracking chamber PC1 consisting of six proportional chamber planes with 2 mm wire spacing; 55 cm of iron magnetized to 16 kG; a second six-plane proportional chamber PC2 with 4 mm wire spacing; a 4 cm thick iron absorber; and, finally, a top scintillator array T. The muon (μ) trigger required a coincidence of the B and T counters with fast analog signals from at least four planes of PC2. The total matter from the source to counter T gave a minimum momentum of 970 MeV/c to trigger the system. The trigger and reconstruction efficiency of the muon arm was 90%.

In the analysis, straight track segments were reconstructed in PC1 and PC2. The PC1 segment was extrapolated to the lowest plane of PC2, and the distance and angle between the PC1 and PC2 segments were determined in both the bend and non-bend projections. A Monte Carlo simulation of the spectrometer, which included ionization loss and multiple scattering of muons, was used to determine contours in the distance-angle space which would contain a certain fraction of muons of given transverse momentum. The momentum acceptance was 50% for $p_T = 0.98$ GeV/c and greater than 90% for $p_T > 1.1$ GeV/c. The probability of an erroneous charge determination was $< 1\%$.

*) We have used the average inclusive cross-sections of π^+ and π^- production as measured by Ref. [5].

Using only the μ trigger, we measured the cross-section seen by the muon spectrometer at $\sqrt{s} = 53$ GeV, and compared it with the known inclusive charged-particle production cross-section [5] integrated over the momentum and geometric acceptance of the spectrometer. The hadron rejection, given by the ratio of known to measured cross-section, is 33 ± 2 . From a Monte Carlo simulation of $\pi \rightarrow \mu\nu$ and $K \rightarrow \mu\nu$ decays, we determined the decay contribution to the measured rate to be 12%. Subtracting it, the observed hadron flux corresponds to an effective attenuation length in iron of (15 ± 0.5) cm.

The $\mu \cdot e$ trigger required the coincidence of a μ trigger with an e trigger from one of the two electron spectrometers. This gave a typical trigger rate of 1 Hz for a luminosity of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. In the analysis, the closest distance of approach of the electron and muon tracks was required to be less than 6 cm, and the point closest to both tracks was required to lie within the beams' interaction region; 7% of events failed these cuts.

The analysis cuts reduced the data sample by a factor of 6000. The E versus p distribution for the electrons of the μe sample, before applying the final lead-glass cut, is shown in fig. 3. In Table 1 the events remaining after all cuts are given for each μe charge combination. The raw excess of oppositely charged μe combinations is $S = (\mu^+ e^- - \mu^- e^+) = 35 \pm 16$ events.

For each of the electron or muon spectrometers there are two types of background: charged particles (misidentified or decaying leptonically) and neutrals (producing lepton pairs). They give rise to two significant background sources for the events of Table 1: charged-charged and charged-neutral.

The charged-charged source is the most pernicious, since we have observed opposite-sign hadron pairs to be more abundant than those of equal sign. We have measured this background directly with special runs taken with a $\mu \cdot H$ trigger, scaled to the luminosity of the μe data and corrected for the hadron rejection of the electron arm. The false signal from this background is 3 ± 2 events. In addition, we have estimated that electrons from K-meson decays contribute less than one event to S .

The charged-neutral background comes almost entirely from a charged source in the muon arm and a neutral source in the electron arm. This background gives most of the observed events. It contributes equally to μ^+e^- and μ^+e^+ , and equally but differently to μ^-e^+ and μ^-e^- . Since the charged source is dominated by pion punch-through and $\pi \rightarrow \mu\nu$ decay, and since the π^+/π^- ratio at $p_T \approx 1$ GeV/c is about 1.2 [5], we expect more of this background to be associated with a μ^+ than with a μ^- . The μ^+e^-/μ^-e^- ratio is indeed consistent with this expectation. The net excess of opposite-sign over same-sign μe events is then 32 ± 16 events after background subtraction. The calculated contribution to S of electrons from Compton scattering of photons in the vacuum chamber is less than one event.

The most likely source of the observed $\mu^\pm e^\mp$ signal is charmed particle production and decay. We henceforth *assume* that the source of the $\mu^\pm e^\mp$ signal is the reaction

$$p + p \rightarrow D + \bar{D} + X . \quad (3)$$

D mesons decay semileptonically into both $\ell K\nu$ and $\ell K^*\nu$ with about equal probability [8]. To compute the detector acceptance, we used the ℓ spectrum of Ali and Yang [9] and assumed equal D branching ratios into the K and K^* decay modes. We further assumed that the p_T and p_L distributions and the rapidity correlation of the D mesons are given by the parametrization of Ref. [7]. A Monte Carlo calculation then gives the geometric and momentum acceptance of our apparatus for μe events as $\epsilon = 1.6 \times 10^{-5}$. The acceptance decreases by a factor of four if the D decay is all into $\ell K^*\nu$ and increases by a factor of two if it is all into $\ell K\nu$. Taking the semileptonic branching fractions of the D into electrons [8,10] and muons as 10% each, we find

$$\sigma(p + p \rightarrow D + \bar{D} + X) = (70 \pm 36) \mu b . \quad (4)$$

The error, primarily due to the statistical uncertainty, does not reflect the model dependence of the acceptance calculation. The acceptance has also been computed assuming the D mesons to be produced independently, each with an inclusive distribution $E d^3\sigma/dp^3 \propto (1-x)^n \exp(-b \cdot m_T)$, where $m_T = (m_D^2 + p_T^2)^{1/2}$ and

$x \approx 2 p_L / \sqrt{s}$. The results for $n = 5$ and $b = 4, 5$, or 6 GeV^{-1} are $\epsilon = 2.3 \times 10^{-5}$, 1.5×10^{-5} , and 1.0×10^{-5} , respectively. The acceptance ϵ changes by 15% per unit change of n .

Comparing our result with the inclusive J/ψ cross-section [3] measured with the same apparatus, we find inclusive $D\bar{D}$ production to be about two orders of magnitude larger. The observed charm production cross-section is compatible with the value [11] obtained at the CERN SPS, and with upper limits [12,13] obtained for lower $\sqrt{s}$ at FNAL and for $\sqrt{s} \approx 55 \text{ GeV}$ at the ISR. However, the result of this experiment is lower than those of two beam-dump experiments [14,15] at $\sqrt{s} = 27.4 \text{ GeV}$.

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Table 1

Muon-electron data separated into charge states.
S is the excess of opposite-sign over same-sign events.

State	Observed events	Hadron background	Subtracted sample
μ^+e^-	85	9 ± 1	76 ± 9
μ^+e^+	64	8 ± 1	56 ± 8
μ^-e^+	67	8 ± 1	59 ± 8
μ^-e^-	53	6 ± 1	47 ± 7
S	35	3 ± 2	32 ± 16

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Figure captions

- Fig. 1 : View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.
- Fig. 2 : Inclusive e/π ratio as a function of c.m. transverse momentum. The lines give the cumulative background expected from a) Compton electrons and K_{e3} decays, b) misidentified hadrons, and c) π^0 and η Dalitz decays. The hatched band indicates the error of the sum of all backgrounds.
- Fig. 3 : Energy and momentum correlation plot for electrons of the final μe sample. There are 269 events in the accepted region.

Fig. 1

Fig. 2

Fig. 3