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**Production of Prompt Electrons in the Charm p_t -region at
 $\sqrt{s} = 630$ GeV.**

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ABSTRACT

The production of prompt electrons at $\sqrt{s} = 630$ GeV has been measured in the p_t range 0.5 - 2.0 GeV/c using a Ring Imaging CHerenkov (RICH) counter installed in the UA2 experiment at the CERN $p\bar{p}$ collider. From our measurement of the electron/hadron ratio in the p_t range 0.9 - 1.5 GeV/c we conclude that the charm production cross-section does not exceed 1.9 mb at 95% CL. As best estimate we obtain $\sigma(c\bar{c}) = 684 \pm 557(\text{stat}) \pm 253(\text{sys,exp}) \pm 205(\text{sys,theory}) \mu\text{b}$. The RICH counter was operated successfully at the collider providing an electron/pion separation capability of better than $8 \cdot 10^{-5}$ at momenta below the pion threshold.

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We report results from a measurement of the prompt-electron production at $\sqrt{s} = 630$ GeV in the p_t range 0.5 - 2 GeV/c, where the decay of charm is expected to be the dominant source. The measurements were carried out at the CERN $p\bar{p}$ collider with a Ring Imaging Cherenkov (RICH) counter [1] for electron identification and a two-plane scintillator hodoscope for triggering and track selection installed in the UA2 detector [2]. This is the first experiment in which a RICH counter has been used at a collider. Fig.1a shows the experimental lay-out, with the RICH counter installed in one of the 12 azimuthal end-cap sectors of UA2, down-stream with respect to the proton beam. The RICH counter covers the polar angle region $20^\circ - 37.5^\circ$ and an azimuthal range of 24° .

A closer view of the RICH counter is shown in fig.1b, which illustrates how the photons radiated by a traversing electron are reflected by the spherical mirror (focal length 600 mm) to form a ring-image in the TPC-type single-photon position detector. The radiator volume is filled with the freon C_2F_6 at atmospheric pressure, implying a π threshold momentum of 3.5 GeV/c.

The π rejection power of the RICH counter was measured in a test beam at the CERN PS [3] where two 4m long threshold Cherenkov-counters were placed in front of the RICH for electron identification. The probability that an incoming electron would be misidentified as a pion by this system (i.e. lack of signal in both counters) was less than $2 \cdot 10^{-7}$. Fig.2 shows the measured probability of misidentifying a pion as an electron in the RICH as a function of the beam momentum, for a constant electron identification efficiency of 60% (closed circles). We have established an additional rejection factor of about 10 from the UA2 electromagnetic calorimeter behind the RICH (see fig 1) giving, below the π threshold, a total rejection better than 10^{-5} (open circles). The π rejection grows worse for momenta above the threshold. In the analysis of the UA2-RICH data we therefore imposed the cut $p < 4$ GeV/c.

Data with the RICH counter mounted in the UA2 set-up were collected during the autumn of 1985. The trigger required signals in both scintillator-hodoscope planes, in coincidence with signals obtained from "forward" scintillators close to the beam on both sides of the collision region. The forward scintillators gave a coincidence signal in more than 98% of all non-diffractive collisions. In addition, the transverse energy deposition measured by the electromagnetic calorimeter, was required to be above a certain threshold. Two different trigger thresholds, 0.8 and 1.4 GeV, were used. Minimum bias triggers, without any requirement on the deposited energy, were recorded simultaneously for normalization purposes. The integrated luminosity is indicated in table 1.

To identify events with prompt electrons and reject triggers from trivial sources, like conversions of photons and Dalitz decays of π^0 and η mesons, a number of requirements were imposed on the two data samples with energy thresholds. These requirements fall into two different categories :

1°. Event selection requirements:

- One single reconstructed track in the RICH sector, with segments measured by the vertex chamber as well as by the drift chambers behind the toroidal magnet, and with signals in the first two layers of the vertex chamber,
- pulse height in both scintillator-hodoscope planes consistent with that expected for a single, minimum-ionizing particle and significantly lower than that expected for two such particles, and
- a good momentum fit with the momentum $p < 4 \text{ GeV}/c$.

2°. Electron identification requirements:

- At least three photons detected within an annular region of width 20 mm centred at the position of the Cherenkov ring expected from the reconstructed track,
- the radius of the circle fitted to the detected photons consistent with 24 mm, as expected for a $\beta = 1$ particle, and
- the energy deposition in the electromagnetic calorimeter consistent with that expected for a single electron with the measured momentum.

To further improve the rejection power of the RICH, all "noisy" events, defined as events containing more than three signals none of which could be assigned to either a traversing track or to a Cherenkov ring, were excluded.

The efficiencies of the electron identification requirements were estimated by Monte Carlo simulation to be as follows:

At least three photons found :	77%
Fitted radius inside $24 \pm 2 \text{ mm}$:	65%
Elimination of noisy events :	90%
Calorimeter requirement :	98%

The inefficiency caused by the RICH is explained by the relatively low number of photons observed per Cherenkov ring (4.5 on the average), and by the strict condition on the fitted radius (non-Gaussian distribution with 3 mm FWHM). The response of the RICH was well reproduced by the Monte Carlo.

Finally, a few events were removed by visual inspection of the detected image. This caused a negligible loss of real electrons.

To obtain the rate of prompt electrons the background from trivial electron sources passing the above cuts must be estimated. The dominant background comes from electron-positron pairs generated by converting photons from the decays of neutral mesons (mostly π^0 and η). Other important sources are the Dalitz decays of π^0 and η and the K_{e3} decays of charged and neutral kaons.

In the first case the electron-positron pair has practically zero mass. Therefore, the conversion partner is likely to be found close to the presumed single-electron candidate. Such events are rejected in the analysis, partly by the single-track requirement and partly by the requirement that the pulse height measured by the scintillator hodoscope in front of the toroidal magnet be inconsistent with that for two charged tracks. Events with hits in the hodoscope

which cannot be associated to the track segment downstream of the magnet are also discarded. Conversions occurring after the photon enters the vertex-chamber region are removed by requiring, for the candidate track, hits in the two inner vertex chambers ("early" hits). The difficult cases are those where one of the electrons is lost before the scintillator hodoscope due to multiple scattering. Many of these events are rejected since the second, non-converted photon deposits energy in the electromagnetic calorimeter.

The above methods eliminate most of the Dalitz decays as well. However, in this case the mass of the electron-positron pair is significantly different from zero which increases the probability for one of the partners escaping our solid angle before crossing the scintillator hodoscope.

The weak decays $K^\pm \rightarrow e^\pm + \pi^0 + \nu$ and $K_L^0 \rightarrow e^\pm + \pi + \nu$ produce single electrons (positrons) which are difficult to distinguish from those originating from the processes $D^\pm \rightarrow e^\pm + X$ and $D^0 \rightarrow e^\pm + X$. The K_L^0 - decays are removed if they occur outside the beam pipe by the requirement of "early" hits on the candidate track. The charged kaon decays are in most cases removed by the requirement of a good momentum fit for the candidate track, since this implies a track pointing at the vertex.

The requirement of "early" hits for the candidate track also removes background from Compton scattering occurring outside the beam pipe.

The residual background remaining after all cuts was calculated by Monte Carlo. For the shape of the π^0 p_t distribution we have used the fit by UA2 [4] to the $p\bar{p} \rightarrow h + X$ data, since this extends to lower p_t values than the $p\bar{p} \rightarrow \pi^0 + X$ measurement. The η/π^0 ratio was taken to be 0.6 ± 0.16 [4]. Finally, the measured ratio $2\pi^0/(h^+ + h^-) = 0.68 \pm 0.13$ [4] was used to convert the residual background e/π^0 ratio into an e/h ratio. The K_{e3} and the Compton contributions were estimated to be negligible compared to the contributions from π^0 and η conversions and Dalitz decays. Fig.3 shows the dominant residual background contributions to the e/h ratio as a function of p_t .

The sample remaining after application of the above selection criteria consists of 14 events with equal numbers of electrons and positrons.

A trigger acceptance correction was calculated, using the Monte Carlo programme to simulate the response of the electromagnetic calorimeter, and applied to obtain the yield of prompt electrons. This corrected electron yield was then normalized to the measured yield of charged hadrons in the same p_t range, obtained by analyzing minimum bias events with the same geometrical acceptance and track-selecting requirements as in the electron case. Only events with a single track in the RICH sector were considered. The resulting sample consisted of 760 minimum bias events in the p_t range 0.5 - 2 GeV/c.

The cuts pertaining to track selection in general introduce losses of equal proportion for the electron (e) sample and for the sample of charged hadrons (h). Hence, their effects cancel out in the ratio e/h .

The measured e/h ratio is presented in table 2 for three momentum bins 0.5 - 0.9, 0.9 - 1.5 and 1.5 - 2.0 GeV/c, the first two corresponding to the trigger with the lower nominal threshold and the last to the trigger with the higher threshold. For $p_t < 0.9$ GeV/c, the trigger acceptance decreases rapidly with p_t resulting in a large systematic error for the ratio e/h . The

results have been corrected for trigger acceptance and electron identification efficiency. The errors quoted are statistical only. The systematic errors, mostly due to uncertainties in the electron identification efficiency and in the trigger acceptance correction, are estimated to be in total $\pm 30\%$, $\pm 13\%$ and $\pm 14\%$, respectively, for the three p_t bins.

The total residual background from π^0 and η conversions and Dalitz decays, expressed in terms of an e/h ratio, is also given in table 2, where the quoted error is mainly systematic.

In the p_t range 0.5 - 0.9 GeV/c the measured e/h is dominated by background. In the p_t range 0.9 - 1.5 GeV/c we have after background subtraction

$$e/h = [2.04 \pm 1.41(\text{stat}) \pm 0.64(\text{sys})] \cdot 10^{-4}$$

and in the range 1.5 - 2.0 GeV/c

$$e/h = [6.35 \pm 4.14(\text{stat}) \pm 1.04(\text{sys})] \cdot 10^{-4}.$$

The systematic error of the measured value and that of the background have been added in quadrature.

The background of misidentified hadrons is small, except for momenta above the pion threshold, hence of importance only in the highest p_t bin. We estimate that in the p_t range 1.5 - 2.0 GeV/c the contribution to the e/h ratio from misidentified hadrons is not larger than $1 \cdot 10^{-4}$. Below 1.5 GeV/c this contribution is at most $9 \cdot 10^{-6}$ and can be neglected.

The above e/h values may be converted into e/π using the π/h ratio of 0.68 ± 0.13 . Including ± 0.13 in the systematic error we obtain for $0.9 < p_t < 1.5$

$$e/\pi = [3.00 \pm 2.07(\text{stat}) \pm 1.32(\text{sys})] \cdot 10^{-4}$$

and for $1.5 < p_t < 2.0$

$$e/\pi = [9.34 \pm 6.09(\text{stat}) \pm 2.51(\text{sys})] \cdot 10^{-4}$$

In the p_t range 0.9 - 1.5 GeV/c, the dominant process contributing to the prompt electron yield is expected to be the semi-leptonic decay of charmed particles. It is thus possible to set an upper limit on the total charm production cross-section by assuming that all our prompt electrons have this origin.

To describe charmed-particle production and semi-leptonic decay characteristics in our kinematical region, a Monte Carlo programme has been used containing the quark-anti-quark and gluon-gluon fusion processes to order α_s^2 [5]. In this programme, the hadronization of the quarks and gluons follows the Lund string-model prescription [6]. This Monte Carlo was used to extrapolate our results to the full phase space and to correct for the restriction in decay topology imposed by the requirement of a single track in the RICH sector. After subtraction of background as described above and applying the Monte Carlo correction we obtain for the electron p_t range 0.9 - 1.5 GeV/c the result

$$\sigma(c\bar{c}) \leq 806 \pm 557(\text{stat}) \pm 253(\text{sys,exp}) \pm 242(\text{sys,theory}) \mu\text{b}.$$

The second systematic error represents the uncertainty in the charm acceptance correction connected with the choice of Monte Carlo parameters.

Adding the different errors in quadrature the upper limit corresponding to a 95% confidence level is

$$\sigma(c\bar{c}) < 1.9 \text{ mb.}$$

Assuming $\sigma(b\bar{b}) \approx 10 \mu\text{b}$ [12] the contribution from semi-leptonic b-decays to the prompt electron signal for $0.9 < p_t < 1.5$ was estimated to be 5%. Using the Pythia Monte Carlo programme [13], the corresponding contribution from decays of the vector mesons ρ , ω , ϕ into e^+e^- was estimated to be about 10 %. The absolute errors in these estimates are small in comparison to other errors. Neglecting them we obtain

$$\sigma(c\bar{c}) = 684 \pm 557(\text{stat}) \pm 253(\text{sys,exp}) \pm 205(\text{sys,theory}) \mu\text{b.}$$

Recently P. Nason et al [7] have published results of a full calculation of the next-to leading order (α_s^3) QCD radiative corrections to the total cross-section for heavy quark-pair hadro-production. Based on these calculations G. Altarelli et al [8] have evaluated the total charm cross-section in pp-collisions up to $\sqrt{s} = 63 \text{ GeV}$. Fig.4 shows the results of the same type of evaluation now extended to $\sqrt{s} = 630 \text{ GeV}$ [9]. In this figure results from the measurements of the total charm production cross-section in pp collisions at energies up to 63 GeV are plotted as well as our $p\bar{p}$ point at 630 GeV. The curves in fig.4 correspond to different values of the charmed quark mass ($1.2 < m_c < 1.8 \text{ GeV}/c^2$) and with different values of the Λ_5 parameter for the gluon structure function ($0.1 < \Lambda_5 < 0.25 \text{ GeV}$). Because of the high $\sqrt{s}$ and the relatively low quark mass in our case, the cross-section is sensitive to the behaviour of the structure functions in regions where no direct measurements exist so far. The value of the scale μ at which $\alpha_s(\mu)$ and the parton densities are calculated is set to 3 GeV. Using lower values for μ like $\mu \approx m_c = 1.5 \text{ GeV}$ decreases the $O(\alpha_s^2) + O(\alpha_s^3)$ cross-sections at $\sqrt{s} = 630 \text{ GeV}$ by about a factor of 2. The significant dependence on the value chosen for μ indicates that even higher order corrections are important.

As compared to the $O(\alpha_s^2)$ calculations the introduction of the $O(\alpha_s^3)$ corrections more than doubles the cross-section in the whole $\sqrt{s}$ range from 10 to 630 GeV. Our cross-section at 630 GeV is consistent with the theoretical expectation although it is clear that within the present theoretical and experimental uncertainties no distinction between the various calculations can be made.

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Figure captions

- Fig.1a A schematic cross-section of one quadrant of the UA2 experiment showing the position of the RICH counter. The outgoing track traverses, in succession, a cylindrical vertex detector (drift chambers and MWPC's) in a region with no magnetic field, the scintillator hodoscope, a toroidal magnetic field, the RICH counter, 3 planar drift chambers, a lead-iron converter (thickness 1.4 radiationlengths) followed by a proportional tube array (not used in this experiment), and enters finally an electromagnetic calorimeter, divided longitudinally into two compartments (24 and 6 radiation lengths, respectively) for better electron/hadron separation. Reconstructed tracks in the vertex detector determine the event vertex which in association with hits in the 3 planar drift chambers is used to measure charged particle momenta.
- Fig.1b Cross-section of the RICH counter in the UA2 showing the photon detector, the spherical mirror and the radiator-gas container.
- Fig.2 The measured probability for misidentifying a pion as an electron, as a function of the particle momentum, using :
the RICH counter alone - closed circles,
the RICH counter combined with the calorimeter - open circles.
- Fig.3 Monte Carlo calculation of the residual background contributions to the e/h ratio as a function of p_t .
- Fig.4 $\sigma(c\bar{c})$ in hadro-production. The open circles correspond to pp measurements [10]. Our $p\bar{p}$ result is marked with a cross and the upper limit corresponding to a 95% confidence level, assuming that all prompt electrons originate from charm decays, is indicated. The curves correspond to next-to-leading order QCD calculations [9] for pp collisions with the following parameters, using DFLM [11] structure-functions:
a) $\Lambda_5=0.170$ GeV $m_c = 1.2$ GeV/ c^2
b) $\Lambda_5=0.170$ $m_c = 1.5$
c) $\Lambda_5=0.170$ $m_c = 1.8$
d) $\Lambda_5=0.250$ $m_c = 1.5$
e) $\Lambda_5=0.101$ $m_c = 1.5$
In all cases $\mu = 3$ GeV.

Table captions

- Table 1 Integrated luminosity and collected number of triggers.
- Table 2 Measured e/h, residual e/h from trivial background sources, and e/h after residual-background subtraction, in units of 10^{-4} .

Table 1

Nominal trigger threshold [GeV]	$\int L dt$ [μb^{-1}]	Number of triggers
–	7.83	$0.06 \cdot 10^6$
0.8	1660	$0.6 \cdot 10^6$
1.4	2720	$0.35 \cdot 10^6$

Table 2

p_t [GeV/c]	$\langle p_t \rangle$	$e/h \cdot 10^4$ measured	$e/h \cdot 10^4$ residual background	$e/h \cdot 10^4$ prompt e
0.5 - 0.9	0.6	$3.42 \pm 1.71 \pm 1.03$	4.45 ± 0.93	$-1.03 \pm 1.71 \pm 1.38$
0.9 - 1.5	1.1	$3.74 \pm 1.41 \pm 0.49$	1.69 ± 0.41	$2.04 \pm 1.41 \pm 0.64$
1.5 - 2.0	1.8	$7.18 \pm 4.14 \pm 1.01$	0.83 ± 0.26	$6.35 \pm 4.14 \pm 1.04$

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

CM energy [GeV]

Fig. 4