D⁰ Production in Deep Inelastic Muon Scattering
on Hydrogen and Deuterium

The European Muon Collaboration

CERN¹-DESY(Hamburg)²-Freiburg³-Kiel⁴-Lancaster⁵-LAPP(Annecy)⁶-Liverpool⁷-
Marseille⁸-Oxford⁹-Rutherford¹⁰-Sheffield¹¹-Turin¹²-Wuppertal¹³

J.J. Aubert⁸, G. Bassompierre⁶, K.H. Becks¹³, C. Benchouk⁸, C. Best^{10a}, E. Böhm⁴,
X. de Bouard⁶, F.W. Brasse², C. Broll^{6*}, S. Brown⁷, J. Carr^{10b}, R.W. Clifft¹⁰,
J.H. Cobb^{5c}, G. Coignet⁶, F. Combley¹¹, G.R. Court⁷, G. D'Agostini⁸, W.D. Dau⁴,
J.K. Davies^{9d}, Y. Déclais^{6e}, U. Dosselli^{1f}, J. Drees¹³, A. Edwards^{13a}, M. Edwards¹⁰,
J. Favier⁶, M.I. Ferrero¹², W. Flauger², H. Forsbach¹³, E. Gabathuler⁷, R. Gamet⁷,
J. Gayler², V. Gerhardt^{2g}, C. Gössling^{2h}, J. Haas³, K. Hamacher¹³, P. Hayman⁷,
M. Henckes¹³ⁱ, V. Korbel², U. Landgraf³, M. Leenen^{1j}, M. Maire⁶, H. Minssieux⁶,
W. Mohr³, H.E. Montgomery^{1k}, K. Moser^{3l}, R.P. Mount^{9m}, E. Nagy⁶ⁿ, J. Nassalski²,
P.R. Norton¹⁰, J. McNicholas^{9o}, A.M. Osborne¹, P. Payre⁸, C. Peroni¹², H. Pessard⁶,
U. Pietrzyk¹³, K. Rith³, M. Schneegans⁶, A. Schneider¹³, T. Sloan⁵, H.E. Stier³,
W. Stockhausen¹³, J.M. Thénard⁶, J.C. Thompson¹⁰, L. Urban⁶ⁿ, M. Villers⁹,
H. Wahlen¹³, M. Whalley^{11p}, D. Williams⁷, W.S.C. Williams⁹, J. Williamson^{11q},
S.J. Wimpenny^{7h}.

ABSTRACT

Inclusive D⁰($\bar{D}^0$) production in deep inelastic scattering of 280 GeV and 240 GeV muons on hydrogen and deuterium targets has been measured; differential cross sections are given and the total cross sections extrapolated to Q²=0. They are compared with the results of photoproduction experiments and with measurements of the muoproduction of charm detected indirectly by multimuon events.

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-
- (a) Now at JET, Joint Undertaking, Abingdon, England.
(b) Now at Lawrence Berkeley Laboratory, Berkeley, California, USA.
(c) Now at University of Oxford, England.
(d) Now at Plessey Defence System, Fareham, England.
(e) Now at Fac. des Sciences de Luminy, Univ. d'Aix-Marseille II, France.
(f) Now at INFN, Sez. Padova, Italy.
(g) Now at Beiersdorf AG, Hamburg, Germany.
(h) Now at CERN, Geneva, Switzerland.
(i) Now at ICR, Köln, Germany.
(j) Now at Physikalisches Institut der Universität Bonn, Bonn, Germany.
(k) Now at FNAL, Batavia, Illinois, U.S.A.
(l) Now at BWB Engineering GmbH, Lörrach, Germany.
(m) Now at California Institute of Technology, Pasadena, California, U.S.A.
(n) Now at Central Research Institute for Physics of the Hungarian Academy of Science, Budapest, Hungary.
(o) Now at GEC Computers, Coventry, England.
(p) Now at Durham University, Durham, England.
(q) Now at RAL, Chilton, Didcot, Oxon, England.
(*) Deceased

Until now, charmed meson production in deep inelastic scattering has been measured indirectly through semileptonic decay, leading to events with 2 or 3 muons in the final state [1,2]. These data are rather sensitive to the c quark fragmentation function and they suffer from backgrounds such as the muonic decays of π and K produced in deep inelastic scattering. The direct observation of muoproduced charmed mesons is desirable to confirm these results. In this paper we present the first direct measurement of inclusive D^0 production, in the reaction

$$\mu + N \rightarrow \mu' + D^0(\bar{D}^0) + X$$

$$\hookrightarrow \pi + K$$

The experiment was performed in the M2 muon beam at the CERN SPS using the EMC forward spectrometer [3] with a 6 metre long target of hydrogen or deuterium. Data were taken in three experimental runs at μ^+ beam energies of 280 GeV and 240 GeV with a hydrogen and at 280 GeV with a deuterium target. The entire length of the target was used for the hydrogen data, while only events having their vertices in the downstream 3 metres were kept for the deuterium data in order to reduce the corrections for secondary interactions. The following cuts were applied to the data: $Q^2 > 3 \text{ GeV}^2$, $40 < \nu < 240 \text{ GeV}$, $\theta_\mu \geq 8 \text{ mrad}^{(*)}$ leaving 251000 deep inelastic events for the D^0 analysis, corresponding to 1.1×10^{12} incident muons. The average Q^2 of these events is 15 GeV^2 . Events were selected with two or more detected hadrons and a scattered muon satisfying the above cuts. The invariant mass of all opposite sign hadron pairs was calculated assuming the kaon and pion mass for each in turn. A neon or nitrogen filled multicell Cerenkov counter [4,5] was used to reject the hadron pairs where the π or K assignment to a track was inconsistent with the information^(**) from the counter. The two body invariant mass resolution of the spectrometer was measured to be 30 MeV FWHM for the observed K^0 peak and estimated by Monte Carlo to be $\sim 55 \text{ MeV}$ for the D^0 mass. Experimentally it was found that the following cuts improved the signal to noise ratio and these cuts were applied:

(*) Q^2 is the negative four-momentum squared of the virtual photon, x_{BJ} the Bjorken variable, θ_μ the muon scattering angle, ν the virtual photon energy, Z the fraction of this energy carried by the D^0 , p_T is the transverse momentum of the D^0 measured with respect to the virtual photon direction.

(**) neon filling; pion (proton) identification region : 26-41 GeV (50-80 GeV)
nitrogen filling; pion (proton) identification region: 7-20 GeV (25-40 GeV)

$$6 < P_{K,\pi} < 150 \text{ GeV/c}$$

and, on the K candidate momentum

for the bin	$0.2 < Z_{\text{pair}} < 0.4,$	$10 < p_K < 80 \text{ GeV/c}$
"	$0.4 < Z_{\text{pair}} < 0.6,$	$20 < p_K < 80 \text{ GeV/c}$
"	$0.6 < Z_{\text{pair}} < 1,$	$20 < p_K < 150 \text{ GeV/c}$

where Z_{pair} is the fraction of the energy of the virtual photon carried by the $K\pi$ pair. In the following, D^0 is taken to mean D^0 or $\bar{D}^0$.

Fig. 1 shows the $K\pi$ invariant mass spectrum for $Z_{\text{pair}} > 0.3$. A clear peak is seen at the D^0 mass with a width compatible with the expected mass resolution. The signal contains $92 \pm 25 D^0$ events (3.7σ) on a background of 440 events, centered at a mass of $1863 \pm 7 \text{ MeV}$; they are equally shared between $K^+\pi^-$ and $K^-\pi^+$ pairs ($50 \pm 16 \bar{D}^0$ and $45 \pm 15 D^0$). This observation indicates that there is not a strong contribution of associated production of D^0 and Λ_c . We also show on the same figure the effect of the cut, $2 < M_{\text{vis}} < 4.5 \text{ GeV}$, where M_{vis} is the invariant mass of all tracks seen in an event. A similar cut of $3 < M_{\text{vis}} < 4 \text{ GeV}$ used in a FNAL photoproduction experiment [6] reduced the background by a factor 2, without loss of D^0 events. In the data presented here, the noise is reduced by a factor 1.5, with no loss of the D^0 signal within the errors. In order not to bias the results, this cut was not applied in the analysis reported here.

To obtain the differential cross sections for inclusive D^0 production the mass spectra were produced in each bin for each distribution presented below. A fit of a smooth polynomial background function in order to extract the D^0 signal was made to each spectrum. The acceptance was calculated by Monte Carlo simulation. Events were generated and weighted according to the photon-gluon fusion (PGF) model (described below) which gives a good description of the charm production data in [1]. Hadrons from the decay of the D^0 and the scattered muon for each event were tracked through the apparatus simulating the effects of secondary interactions in the target, chamber and hodoscope efficiencies,

multiple scattering and measurement errors. Each generated event was accepted if it fulfilled the trigger requirement and would have been detected in the forward spectrometer. The mean acceptance ($Q^2 > 3 \text{ GeV}^2$) is 11%. The branching ratio for $D^0 \rightarrow K\pi$ was assumed to be 0.03 throughout [16] although there is some uncertainty with regard to this value [11].

The cross section $d\sigma/dZ$ for $\mu+p \rightarrow \mu'+D^0+x$ is shown in fig. 2a where the error bars are statistical. The smooth curves show the absolute predictions of the PGF model for two different fragmentation functions. In this model the virtual photon, is assumed to interact with a $c\bar{c}$ pair produced by a gluon in the target. The formulae were taken from Leveille and Weiler [7], with the parameters given in [1]. It was assumed that one D^0 or $\bar{D}^0$ is emitted on average for each $c\bar{c}$ pair (as predicted by the Lund string model for the fragmentation process [10]). The solid curve in fig. 2a shows the absolute prediction of the PGF model using a fragmentation function, $\exp(1.6 Z_c)$, as obtained in [1], where Z_c is the fraction of the energy of the charmed quark in the laboratory frame carried by the D^0 meson. The dashed curve shows the prediction for the fragmentation function proposed in [8]:

$$D(Z_c) = [Z_c(1 - \frac{1}{Z_c} - \frac{\epsilon}{1-Z_c})^2]^{-1}$$

where ϵ was taken to be 0.11, the value obtained in a common fit to neutrino and e^+e^- data [9]. The data are consistent with these "hard" fragmentation functions, but are insufficiently precise to distinguish between them. Nevertheless diffractive $D^0\bar{D}^0$ pair production leading to a flat Z distribution is excluded. A mechanism such as the virtual photon striking a single charmed quark, as in the conventional picture of deep inelastic scattering, would give a Z distribution similar to that seen in e^+e^- collisions i.e. peaking at $Z \sim 0.7$. Thus the data are more compatible with the predictions of the PGF model where the energy of virtual photon is shared between two charmed quarks than the transfer to a single struck quark.

Fig. 2b shows the measured values of $d\sigma/dp_T^2$. The solid curve shows the prediction of the PGF model which tends to deviate from the data at large p_T .

Fig. 3 shows the acceptance corrected number of D^0 per scattered muon, for $Q^2 > 3 \text{ GeV}^2$ and $Z > 0.2$, as a function of x_{BJ} . The curve shows the prediction of the PGF model which is consistent with the data. Extrapolating to $Z=0$ using the PGF model, gives $N_{D^0}/N_\mu' = 0.11 \pm 0.03$ where N_μ' is the number of scattered muons and the error is purely statistical. This is in reasonable agreement with the value of ~ 0.07 at $Q^2 = 15 \text{ GeV}^2$, expected from the multimMuon measurements [1], assuming that one D^0 meson is produced per charmed quark pair. Recent results from the HRS experiment [12] at PEP indicate a value of 0.5 D^0 mesons per charmed quark pair. Such a value would reduce the value of N_{D^0}/N_μ' expected from the multimMuon data by a factor 2 and would therefore be inconsistent with the data presented here. More recent measurements of the branching ratio of $D^0 \rightarrow K\pi$ [11] give values $\sim 5\%$. With such a branching ratio the measured value of N_{D^0}/N_μ' would be 0.066 ± 0.018 which is more consistent with that expected from the multimMuon data.

In order to compare the data with those obtained in experiments with real photons, the total photoproduction cross section at $Q^2=0$ for the reaction $\gamma + N \rightarrow D^0 + X$ as a function of the photon energy was derived as follows. The differential cross section for muoproduction can be written in the form,

$$\frac{d^2\sigma}{dQ^2 dv} = \Gamma(Q^2, v) \sigma_Y(Q^2, v)$$

where Γ is the flux of virtual photons according to the Hand convention [15], and $\sigma_Y(Q^2, v)$ is the virtual photoproduction cross section. The latter can be parameterised in the form:

$$\sigma_Y(Q^2, v) = \frac{\sigma_Y(Q^2=0, v)}{(1+Q^2/M^2)^2}$$

which gave a good fit to the data in [1]. The value of M was fixed to be 3.9 GeV, the average of the values found in [1]. Integrating over Q^2 from 3 GeV^2 to Q_{max}^2 , the kinematic limit, gives

$$\left(\frac{d\sigma}{dv}\right)_{Q^2 > 3} = \sigma_Y(Q^2=0, \nu) \int_{Q^2=3}^{Q^2_{\max}} \frac{\Gamma(Q^2, \nu)}{(1+Q^2/M^2)^2} dQ^2 .$$

$\sigma_Y(Q^2=0, \nu)$ is obtained by extracting $\frac{d\sigma}{dv}$ from the data for 3 ν bins (40-110, 110-180, 180-240 GeV) and computing the integral numerically. The values of $\sigma_Y(Q^2=0)$ are shown as a function of ν in fig. 4 together with the multimuron data [1,2] and the results of photoproduction experiments. The agreement between the different experiments is good. The agreement between the multimuron results and those obtained from direct D^0 production is consistent with the assumption of one D^0 meson produced in the fragmentation of each charmed quark pair. The smooth curve in fig. 4 shows the absolute prediction of the PGF model which gives a good representation of the data.

In conclusion, the results from the direct observation of charmed meson production in deep inelastic muon scattering confirm the indirect measurements of the multimuron data and are also consistent with real photoproduction measurements. Given that the fragmentation for charmed quarks is hard, the observed rather soft Z distribution implies that the virtual photon energy is shared by more than one quark, and is not transferred to a single charmed quark inside the nucleon, leaving the remaining quark as a spectator in the target fragments. The results are also not consistent with diffractive production of D^0 and $\bar{D}^0$ meson pairs. The observation of approximately equal numbers of D^0 and $\bar{D}^0$ mesons implies that the fragmentation process is not dominated by associated production of D^0 's and Λ_c 's in the energy range of this experiment.

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FIGURE CAPTIONS

Fig. 1) The $K\pi$ invariant mass distribution with and without the cut $2 < M_{vis} < 4.5$ GeV.

Fig. 2a) The cross section $\frac{d\sigma}{dz_{D^0}}$ for the inclusive reaction $\mu+p \rightarrow \mu' + D^0 + X$ at $Q^2 > 3 \text{ GeV}^2$. The solid line is the absolute prediction of the PGF model with parameters used in Ref. [1] and a charm fragmentation function $D(Z_c) = \exp(1.6 Z_c)$. The dashed line is the same model using $D(Z_c) = 1/[Z_c(1-1/Z_c-0.11/(1-Z_c))^2]$ [8]. In both cases, one D^0 is assumed to be produced per $c\bar{c}$ quark pair, and a 3% branching ratio is assumed for the decay $D^0 \rightarrow K\pi$.

Fig. 2b) The inclusive cross section, $d\sigma/dp_T^2$ of the D^0 for $Z_{D^0} > 0.2$; the solid line is the prediction of the PGF model with a fragmentation function, $\exp(1.6 Z_c)$ with an arbitrary normalisation.

Fig. 3 The fraction N_{D^0}/N_μ of produced D^0 per scattered muon as a function of X_{BJ} for $Z_D > 0.2$ and $Q^2 > 3 \text{ GeV}^2$. The smooth curve is the prediction of PGF model (arbitrary normalisation).

Fig. 4 The total charm photoproduction cross section ($Q^2=0$) as a function of the photon energy.

- this experiment (EMC) in $\gamma_v + N \rightarrow D^0(\bar{D}^0) + X$
- ▼ EMC MultimMuon results [1] in $\gamma_v + Fe \rightarrow c\bar{c} + X$
- ▼ BFP MultimMuon results [2] in $\gamma_v + Fe \rightarrow c\bar{c} + X$
- Δ SLAC results [13] in $\gamma + p \rightarrow c\bar{c} + X$
- X WA4 Collaboration [14] in $\gamma + p \rightarrow \bar{D}^0 + X$
- CIF FNAL [6] in $\gamma + (CH) \rightarrow D^0(\bar{D}^0) + X$

The D^0 results are evaluated with a 3% branching ratio for $D^0 \rightarrow K\pi$.

FIG. 1

FIG. 2b

FIG. 3

FIG. 4