Measurement of charm fragmentation fractions in PHP and the production of the excited charm mesons at HERA *

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Abstract

The production of D^*, D^+, D^0, D_s^+ and Λ_c charm hadrons and their antiparticles in ep scattering at HERA has been studied with the ZEUS detector, using a total integrated luminosity of $372pb^{-1}$. The fractions of charm quarks hadronising as a particular charm hadron were derived. In addition, the ratio of neutral to charged D-meson production rates, the fraction of charged D-mesons produced in a vector state, and the strangeness-suppression factor have been determined. The measurement has been performed in the photoproduction regime. The charm fragmentation fractions are compared to previous results from HERA and from e^+e^- experiments. The data support the hypothesis that fragmentation is independent of the production process.

The production of the excited charm mesons $D_1(2420)$ and $D_2^*(2460)$ in ep collisions has been measured with the ZEUS detector at HERA using the same integrated luminosity. The masses of the neutral and charged states, the widths of the neutral states, and the helicity parameter were determined and compared with other measurements and with theoretical expectations. Ratios of branching fractions of the two decay modes of the $D_2^*(2460)$ states were measured and compared with previous measurements. The fractions of charm quarks hadronising into D_1 and D_2^* were measured and are consistent with those obtained in e^+e^- annihilations.

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1 Introduction

The production of the well-established ground-state charm mesons D and D^* has been extensively studied in ep collisions at HERA. In this paper, measurements of the photoproduction of charm hadrons in ep collisions at HERA are presented.The relative production rates of the most copiously produced charm ground states, the D^0, D^+, D_s^+ mesons and the Λ_c baryon, and of the D!+ meson were measured.1 The fractions of charm quarks hadronising into a particular charm hadron, $f(c \rightarrow D, D^*, \Lambda_c)$ were determined in the kinematic range of transverse momentum $p_T(D, D^*, \Lambda_c) \geq 3.8GeV$ and pseudorapidity $\eta(D, D^*, \Lambda_c) \leq 1.6$ of the charm state. Here D stands for D^0, D^+ and D_s^+ mesons. In addition, the ratio of neutral to charged D-meson production rates, the fraction of charged D mesons produced in a vector state, and the strangeness-suppression factor were determined. The fragmentation universality can be tested by measuring the fragmentation fractions at HERA and comparing the results with those obtained with e^+e^- collisions. Additionally, the values of the fragmentation fractions are crucial parameters used in comparisons of perturbative QCD (pQCD) calculations with measurements of charm production at HERA and elsewhere.

The large charm production cross section at HERA makes it possible to also investigate the excited charm-meson states. The analysis was performed using data taken from 2003 to 2007, when HERA collided electrons or positrons at 27.5 GeV with protons at 920 GeV. The data correspond to an integrated luminosity of $373pb^{-1}$. The upgraded ZEUS detector included a microvertex detector, allowing the measurement of the decay vertex of charm mesons. In particular, the signal-to-background ratio was significantly improved for the D^+ meson, which has the highest lifetime among the charm hadrons. To maximise the statistics, both photoproduction and deep inelastic scattering events were used in this analysis. Events produced in the photoproduction regime contributed $70-80\%$ of the selected charm-meson samples. In a previous ZEUS analysis [1], with an integrated luminosity of $126pb^{-1}$, the orbitally excited states $D_1(2420)^0$ with $JP = 1^+$ and $D_2(2460)^0$ with $JP = 2^+$ were studied in the decay modes $D_1(2420)^0 \rightarrow D^*(2010)^+\pi^-$ and $D_2^*(2460)^0 \rightarrow D(2010)^+\pi^-, D^+\pi^-$. In this paper the analysis was repeated with an independent data sample of higher integrated luminosity. In addition the production of the charged excited charm mesons $D_1(2420)^+$ and $D_2^*(2460)^+$ was studied for the first time at HERA in the decay modes $D_1(2420)^+ \rightarrow D^*(2007)^0\pi^+$ and $D_2^*(2460)^+ \rightarrow D^*(2007)^0\pi^+, D_0\pi^+$. For both the neutral and charged excited charm mesons the study also includes a measurement of fragmentation fractions and ratios of the D_2^* branching fractions.

2 Experimental set-up

A detailed description of the ZEUS detector can be found elsewhere [2]. In the kinematic range of the analysis, charged particles were tracked in the central tracking detector (CTD) and the microvertex detector (MVD). These components operated in a magnetic field of 1.43T provided by a thin superconducting solenoid. The CTD consisted of 72 cylindrical drift-chamber layers, organised in nine superlayers covering the polar-angle region $15^\circ \leq \theta \leq 164^\circ$. The MVD silicon tracker consisted of a barrel (BMVD) and a forward (FMVD) section. The BMVD contained three layers and provided polar-angle coverage for tracks from 30° to 150°. The four-layer FMVD extended the polar-angle coverage in the forward region to 7°. After alignment, the single-hit resolution of the MVD was $24\mu m$. The high-resolution uraniumscintillator calorimeter (CAL) consisted of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part was subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter was called a cell.

The luminosity was measured using the Bethe-Heitler reaction $ep \to e\gamma p$ by a detector which consisted of an independent leadscintillator calorimeter and a magnetic spectrometer system.

3 Charm fragmentation fractions

Charm hadrons were reconstructed using CTD-MVD tracks. Combinations of good tracks were used to form charm-hadron candidates. To ensure good momentum resolution, each track was required to reach at least the third superlayer of the CTD. The D^0 mesons were reconstructed using the decay mode $D^0 \to K^-\pi^+$. In each event, tracks with opposite charges and pT ¿ 0.8GeV were combined in pairs to form D0 candidates. The nominal kaon and pion masses were assumed in turn for each track and the invariant mass of the pair, $M(K\pi)$, was calculated. The kaon and pion tracks, measured precisely in the CTD-MVD detector system, were used to reconstruct the decay point of the D^0 meson.The relatively long lifetime of the D^0 meson resulted in a secondary vertex that is often well separated from the primary interaction point. This property was exploited to improve the signal-to-background ratio. Figure 1 shows the $M(K\pi)$ distribution for D^0 candidates. The corresponding D^0 candidate was assigned to the class of candidates with ΔM tag if the mass difference, $\delta M = M(K\pi\pi_s) - M(K\pi)$ was in the range $0.143 \leq \Delta M \leq 0.148 GeV$. Clear signals are seen at the nominal value of the D^0 mass with and without ΔM tag.

The D^+ mesons were reconstructed using the decay mode $D^+ \to K^-\pi^+\pi^+$. In each event, two tracks with the same charge and $p_T \geq 0.5GeV$ and a third track with the opposite charge and $p_T \geq 0.7GeV$ were combined to form D^+ candidates. Figure 2 shows the $M(K\pi\pi)$ distribution for the D^+ candidates after all cuts. A clear signal is seen at the nominal value of the D^+ mass. The sum of two Gaussian functions with the same peak position was used to describe the signal.The D_s^+ mesons were reconstructed using the decay mode $D_s^+ \to \phi\pi^+$ with $\phi \to K^+K^-$.

For the determination of the fragmentation fractions of the D^*, D^+, D^0, D_s^+

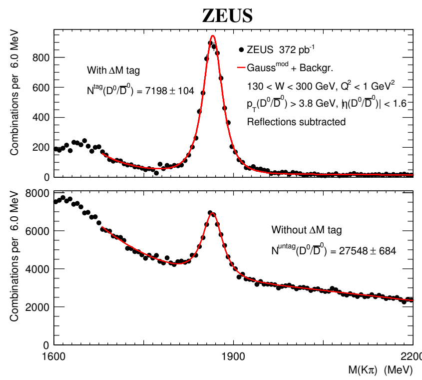

Figure 1: The $M(K\pi)$ distribution for (a) the D^0 candidates with ΔM tag, and for (b) the D^0 candidates without ΔM tag

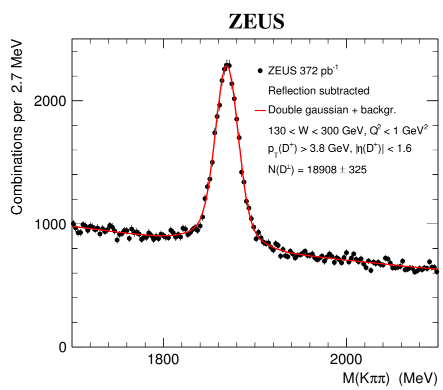

Figure 2: The $M(K\pi\pi)$ distribution for the D^+ candidates.

	ZEUS (γp) (prel.) HERA II	ZEUS (γp) HERA I	H1 (DIS)	ZEUS (DIS) HERA I	Combined e^+e^- data
	stat. syst. br.	stat. syst. br.	stat.⊕syst. br.	stat. syst. br.	stat.⊕syst. br.
$f(c \to D^+)$	$0.232 \pm 0.006 ^{+0.005}_{-0.006} {}^{+0.009}_{-0.010}$	$0.222 \pm 0.015 ^{+0.014}_{-0.005} {}^{+0.011}_{-0.013}$	$0.204 \pm 0.026 ^{+0.009}_{-0.010}$	$0.217 \pm 0.018 ^{+0.002}_{-0.019} {}^{+0.009}_{-0.010}$	$0.222 \pm 0.010 ^{+0.010}_{-0.009}$
$f(c \to D^0)$	$0.590 \pm 0.016 ^{+0.011}_{-0.007} {}^{+0.013}_{-0.019}$	$0.532 \pm 0.022 ^{+0.018}_{-0.017} {}^{+0.019}_{-0.028}$	$0.584 \pm 0.048 ^{+0.018}_{-0.019}$	$0.585 \pm 0.019 ^{+0.009}_{-0.052} {}^{+0.018}_{-0.019}$	$0.544 \pm 0.022 ^{+0.007}_{-0.007}$
$f(c \to D_s^+)$	$0.089 \pm 0.005 ^{+0.002}_{-0.007} {}^{+0.005}_{-0.005}$	$0.075 \pm 0.007 ^{+0.004}_{-0.004} {}^{+0.005}_{-0.005}$	$0.121 \pm 0.044 ^{+0.008}_{-0.008}$	$0.086 \pm 0.010 ^{+0.007}_{-0.008} {}^{+0.005}_{-0.005}$	$0.077 \pm 0.006 ^{+0.005}_{-0.004}$
$f(c \to \Lambda_c^+)$	$0.078 \pm 0.012 ^{+0.005}_{-0.009} {}^{+0.024}_{-0.014}$	$0.150 \pm 0.023 ^{+0.014}_{-0.022} {}^{+0.038}_{-0.025}$		$0.098 \pm 0.027 ^{+0.020}_{-0.017} {}^{+0.025}_{-0.023}$	$0.076 \pm 0.007 ^{+0.027}_{-0.016}$
$f(c \to D^{*+})$	$0.234 \pm 0.006 ^{+0.004}_{-0.004} {}^{+0.005}_{-0.007}$	$0.203 \pm 0.009 ^{+0.008}_{-0.006} {}^{+0.007}_{-0.010}$	$0.276 \pm 0.034 ^{+0.009}_{-0.012}$	$0.234 \pm 0.011 ^{+0.006}_{-0.021} {}^{+0.007}_{-0.010}$	$0.235 \pm 0.007 ^{+0.003}_{-0.003}$

Figure 3: Fractions of charm quarks hadronising as a particular charm hadron, $f(c \to D, D^*, \Lambda_c)$

and Λ_c charm ground states, the total cross section for charmed hadron production is needed. In this cross section, the production cross sections of the charm-strange baryons must also be included. Since these charm-strange baryons do not decay into Λ_c, a correction is needed. The production rates for these baryons are expected to be much lower than that of the Λ_c due to strangeness suppression. The relative rates for the ground states of the charm-strange baryons were estimated from the non-charm sector following the LEP procedure. The total rate for the three charm-strange baryons relative to the Λ_c state is expected to be about 14%. Therefore the Λ_c production cross section was scaled by the factor 1.14. The charm fragmentation fractions, measured in the kinematic region $Q^2 \leq 1GeV^2$, $130 \leq W \leq 300GeV$ are summarised in Fig.3. These results have been computed using the PDG 2012 branching-ratio values. The measurements are compared to previous HERA results and to the combined fragmentation fractions for charm production in e^+e^- annihilations.

This comparison is also shown in Figure 4. The obtained precision of the fragmentation fractions is competitive with measurements in e^+e^- collisions. All data from ep and e^+e^- collisions are in agreement with each other. This demonstrates that the fragmentation fractions of charm quarks are independent of the production process and supports the hypothesis of universality of heavy-quark fragmentation.

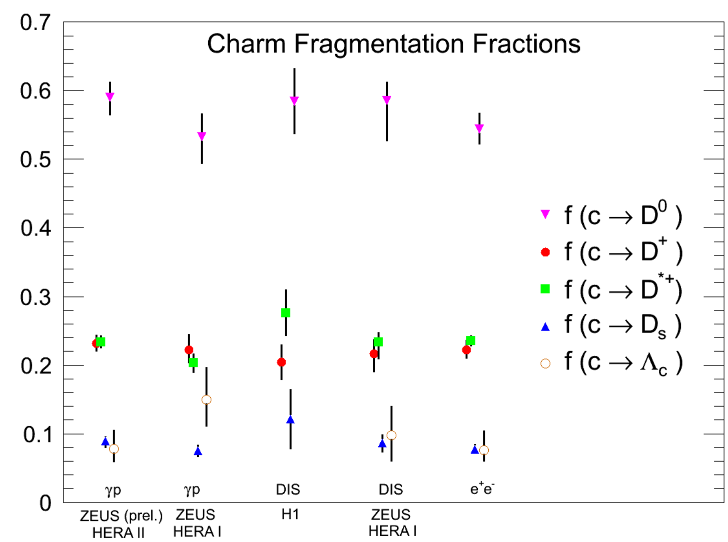

Figure 4: Fractions of charm quarks hadronising as a particular charm hadron. The photoproduction measurements presented in this paper are shown (first column) and compared to previous HERA results in photoproduction (second column), DIS (third and fourth column) and to e^+e^- data (last column), with statistical, systematic and branching-ratio uncertainties added in quadrature.

4 Production of the excited charm mesons

The production of the excited charm mesons $D_1(2420)^0$ and $D_2(2460)$ in ep collisions has been measured with the ZEUS detector at HERA using an integrated luminosity of $373pb^{-1}$ [3]. The masses of the neutral and charged states, the widths of the neutral states, and the helicity parameter of $D_1(2420)^0$ were determined and compared with other measurements and with theoretical expectations. Excited D-mesons were identified via different decay modes. E.g., Figure 5 shows the ΔM distributions for the D^+ candidates. Figure 6 shows the mass distributions for the D_1^0 and D_2^* candidates.

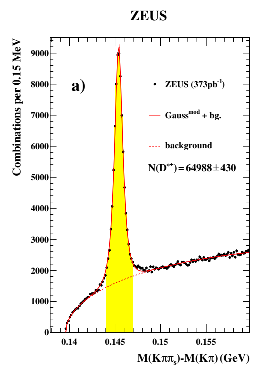

Figure 5: The distribution of the mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$

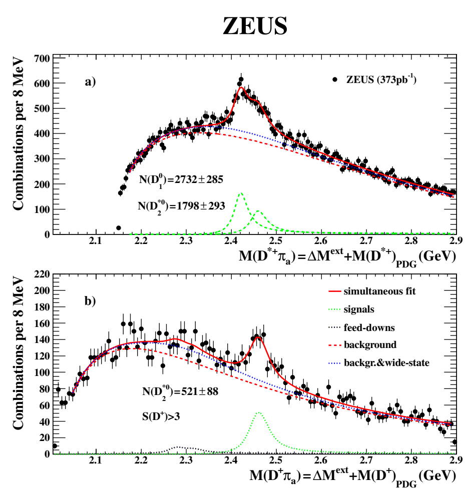

Figure 6: The distribution of the mass distributions for the D_1^0 and D_2^* candidates

The results of the simultaneous fit are given in Figs. 7 and 8. The masses of both D_1^0 and D_2^* are consistent with the PDG values and with a recent BABAR measurement.

$h(D_2^{*0})$	HERA II	HERA I	PDG
$N(D_1^0 \to D^{*+}\pi)$	2732 ± 285	3110 ± 340	
$N(D_2^{*0} \to D^{*+}\pi)$	1798 ± 293	870 ± 170	
$N(D_2^{*0} \to D^{+}\pi)$	521 ± 88 $(S(D^+) > 3)$	690 ± 160	
$M(D_1^0)$, MeV	$2423.1 \pm 1.5^{+0.4}_{-1.0}$	$2420.5 \pm 2.1 \pm 0.9$	2421.3 ± 0.6
$\Gamma(D_1^0)$, MeV	$38.8 \pm 5.0^{+1.9}_{-5.4}$	$53.2 \pm 7.2^{+3.3}_{-4.9}$	27.1 ± 2.7
$h(D_1^0)$	$7.8^{+6.7+4.6}_{-2.7-1.8}$	$5.9^{+3.0+2.4}_{-1.7-1.0}$	
$M(D_2^{*0})$, MeV	$2462.5 \pm 2.4^{+1.3}_{-1.1}$	$2469.1 \pm 3.7^{+1.2}_{-1.3}$	2462.6 ± 0.7
$\Gamma(D_2^{*0})$, MeV	$46.6 \pm 8.1^{+5.9}_{-3.8}$	43 fixed	49.0 ± 1.4
	-1 fixed	-1 fixed	
$D_1(2430)^0/D_1^0$	1.0 fixed	1.0 fixed	
$D_0^*(2400)^0/D_2^{*0}$	1.1 ± 1.1	1.7 fixed	
Feed-downs$/D_2^{*0}$	0.3 ± 0.4		

Figure 7: Results of the simultaneous fit for the yields (N), masses (M), widths (Γ) and helicity parameters (h) of the D_1^0 and D_2^* mesons

	HERA II	PDG
$N(D_1^+ \to D^{*0}\pi^+)$	759 ± 183	
$N(D_2^{*+} \to D^{*0}\pi^+)$	634 ± 223	
$N(D_2^{*+} \to D^{0}\pi^+)$	737 ± 164	
$M(D_1^+)$, MeV	$2421.9 \pm 4.7^{+3.4}_{-1.2}$	2423.4 ± 3.1
$\Gamma(D_1^+)$, MeV	25 fixed	25 ± 6
$h(D_1^+)$	3.0 fixed	
$M(D_2^{*+})$, MeV	$2460.6 \pm 4.4^{+3.6}_{-0.8}$	2464.4 ± 1.9
$\Gamma(D_2^{*+})$, MeV	37 fixed	37 ± 6
$h(D_2^{*+})$	-1.0 fixed	

Figure 8: Results of the simultaneous fit for the yields (N), masses (M), widths (Γ) and helicity parameters (h) of the D_1^+ and D_2^{*+} mesons

5 Summary and outlook

We have investigated the charm hadrons and excited charm hadrons production. The full HERA data taken from 2003 to 2007 with an integrated luminosity of $373pb^{-1}$ has been used to studies. The photoproduction of the charm hadrons $D^{*}, D^{+}, D^{0}, D_{s}^{+}$ and Λ_{c} and their corresponding antiparticles has been measured with the ZEUS detector. The fractions of charm quarks hadronising as $D^{*}, D^{+}, D^{0}, D_{s}^{+}$ and Λ_{c} hadrons have been determined. The precision of the fragmentation fractions obtained is competitive with measurements in e+e collisions. All data from ep and $e^{+}e^{-}$ collisions are in agreement with each other. This demonstrates that the fragmentation fractions of charm quarks are independent of the production process and supports the hypothesis of the universality of heavy-quark fragmentation.

Signals of $D_{1}(2420)^{0}$ and $D_{2}(2460)^{0}$ were seen in the $D(2010)^{+}\pi^{-}$ decay mode and a clear $D_{2}^{*}(2460)^{0}$ signal was seen in the $D^{+}\pi^{-}$ decay mode. The measured D_{1}^{0} and D_{2}^{*} masses and widths are in good agreement with the latest PDG values. A clear $D_{2}^{*}(2460)^{+}$ signal is seen for the first time at HERA.

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