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# Production of the excited charm mesons $D_1$ and $D_2^*$ at HERA

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The production of the excited charm mesons $D_1$ and $D_2^*$ in $ep$ collisions has been measured with the ZEUS detector at HERA. The data sample taken by the ZEUS detector in the years 2003-2007, corresponding to an integrated luminosity of $373\,\text{pb}^{-1}$ has been used. The masses of the neutral and charged, the widths of the neutral states and the helicity parameters of $D_1^0$ were determined and compared with other measurements and with theoretical expectations. The measured helicity parameter of the $D_1^0$ allows for some mixing of $S$- and $D$-waves in its decay to $D^{*\pm}\pi^{\mp}$. The measured value of the $D_1^0$ helicity parameter is also consistent with a pure $D$-wave decay. Ratios of branching fractions of the two decay modes of the $D_2^*$ 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 lowest-mass states of the $c\bar{u}$, $c\bar{d}$ and $c\bar{s}$ systems with orbital angular momentum $L$=0 and spin $S$=0 ($D^0$, $D^+$, $D_s^+$) and $S$=1 ($D^{*0}$, $D^{*+}$, $D_s^{*+}$) [1] are well established [1]. For higher, "excited", states with $L$=1, four states are expected for each $c\bar{q}$ system: one state with $S$=0 and three states with $S$=1. This makes one state with $J^P$=$0^+$, one with $J^P$=$2^+$ and two with $J^P$=$1^+$. The $L$=1 mesons can decay via the strong interaction to charm mesons with $L$=0 by emitting one or more pions or kaons. According to Heavy Quark Effective Theory (HQET) [2, 3], the properties of the $L$=1 mesons are determined mainly by the total angular momentum of the light quark, $j$=$\ell$+$s$, where $s$ denotes the spin of the light quark. On this basis, the four states are grouped in doublets with $j$=3/2 and $j$=1/2. The HQET predicts different properties for those doublets. The $j$=3/2 mesons are allowed to decay only via $D$-wave decays and $j$=1/2 mesons are allowed to decay only via $S$-wave decays. In the same time the states with $J^P$=$1^+$ can mix. The same mixing, between $S$- and $D$-waves, occurs in the decays of $J^P$=$1^+$ to $D^*$. The mixing can be measured from the angular distribution of the decay products. For $D_1^0 \to D^*\pi_a, D^* \to D^0\pi_s$ decay, for example, the latter can be parametrised as $\mathrm{d}\Gamma_{D_1}/\mathrm{d}\cos\alpha \propto 1+h\cos^2\alpha$, where $\alpha$ is an angle between $\pi_s$ and $\pi_a$ in the $D^*$ rest-frame and $h$ is called helicity parameter. This parameter depends on $r=\frac{\Gamma_S}{\Gamma_S+\Gamma_D}$, the relative fraction of the $S$-wave decay and $\phi$, the phase between $S$- and $D$-wave decay amplitudes. The relation between $h$, $r$ and $\phi$ is given by the equation

$$\cos\phi = \frac{(3-h)/(3+h)-r}{2\sqrt{2r(1-r)}}. \tag{1.1}$$

The expected angular distribution for a pure $D$-wave correspond to $h$=3 for $D_1 \to D^*\pi$ and $h$=−1 for $D_2^* \to D^*\pi$.

## 2. $D^{*+}$, $D^+$ and $D^0$ reconstruction

The reconstruction of the candidates was performed by combining of selected tracks to form vertices [4,5]. The selection of candidates for each particular mode was mainly driven by the requirement of a clear signal for the excited charm states. To enhance the signal-to-background ratio, cuts on the quality of track and vertex reconstruction were applied, including particle identification for the tracks and the lifetime tagging for the vertices. To select a region with a reasonable detector acceptance, cuts on $p_T$ and $\eta$ of reconstructed $D^0$, $D^+$ and $D^{*+}$ candidates were applied.

$D^{*+}$ mesons were identified via the decay modes $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+$ and $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^-\pi^+)\pi_s^+$, where $\pi_s$ is a low-momentum ("soft") pion, due to the small mass difference between $D^{*+}$ and $D^0$. The invariant mass of the candidate was calculated assuming pion and kaon mass hypothesis for the track. Fig. 1(a,b) shows the $\Delta M = M(K\pi\pi_s) - M(K\pi)$ and $\Delta M = M(K\pi\pi\pi\pi_s) - M(K\pi\pi\pi)$ distributions for $D^{*+}$ candidates after selection. Clear peaks are seen at the nominal value of $M(D^{*+}) - M(D^0)$ [1].

[1] Charged conjugation states are always included.

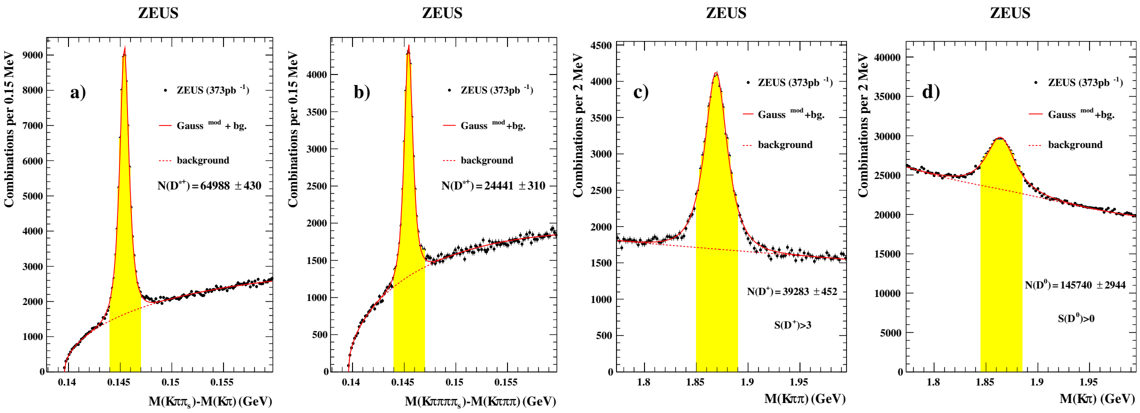


**Figure 1:** *The distribution of the mass difference (dots), (a)* $\Delta M = M(K\pi\pi_s) - M(K\pi)$*, (b)* $\Delta M = M(K\pi\pi\pi\pi_s) - M(K\pi\pi\pi)$*, (c)* $M(K^-\pi^+\pi^+)$ *for events with significance* $S>3$ *and (d)* $M(K^-\pi^+)$ *for events with significance* $S>0$*. The solid curves are fits to the sum of a modified Gaussian function and a background function (dashed lines). Events from the shaded area, (a),(b)* $0.144-0.147\,GeV$*, (c)* $1.85-1.89\,GeV$ *and (d)* $1.845-1.885\,GeV$*, are used for the excited-charm-mesons analysis.*

The $\Delta M$ distributions were fitted to a sum of a background function and a modified Gaussian function [6]. The fit yielded[2] $D^{*+}$ signals of 64988±430 candidates for $D^0 \to K\pi$ and 24441±310 candidates for $D^0 \to K\pi\pi\pi$.

$D^+$ mesons were reconstructed from the decay $D^+ \to K^-\pi^+\pi^+$ with looser kinematic cuts than in a previous analysis [6], made possible by the cleaner identification with the installed silicon tracker. For each event, track pairs with equal charge and pion mass assignment were combined with a track with opposite charge and a kaon mass assignment to form a $D^+$ candidate. These tracks were refitted to a common decay vertex, and the invariant mass, $M(K\pi\pi)$, was calculated. A clear signal is seen (Fig. 1(c)) at the nominal value of the $D^+$ mass [1]. The mass distribution was fitted to a sum of a modified Gaussian function and a polynomial background. The fit yielded[2] a $D^+$ signal of 39283±452 events.

$D^0$ mesons were reconstructed from the decay $D^0 \to K^-\pi^+$. For each event, two tracks with opposite charge and with $K$ and $\pi$ mass assignments, respectively, were combined to form a $D^0$ candidate. These tracks were refitted to a common decay vertex, and the invariant mass, $M(K\pi)$, was calculated. $D^0$ candidates which are consistent with a $D^{*+} \to D^0\pi_s^+$ decay, when combined with a third "soft" pion $\pi_s$ were removed by requiring $M(K\pi\pi_s) - M(K\pi) > 0.15$GeV. A clear signal is seen (Fig. 1(d)) at the nominal value of the $D^0$ mass [1]. The mass distribution was fitted to a sum of a modified Gaussian function, a broad modified Gaussian representing the reflection produced by $D^0$ mesons with the wrong (opposite) kaon and pion mass assignment and a polynomial background. The fit yielded[2] a $D^0$ signal of 145740±2944 events.

[2]The number of signal candidates was obtained as an integral of the fitted modified Gaussian function over the fit range.

## 3. $D_1(2420)^0$ and $D_2^*(2460)^0$ reconstruction

The $D_1^0$ and $D_2^{*0}$ mesons were reconstructed in the decay mode $D^{*+}\pi^-$ by combining each $D^{*+}$ candidate with an additional track, assumed to be a pion ($\pi_a$), with a charge opposite to that of the $D^*$. For each excited-charm-meson candidate, the "extended" mass difference, $\Delta M^{\rm ext} = M(K\pi\pi_s\pi_a) - M(K\pi\pi_s)$ or $\Delta M^{\rm ext} = M(K\pi\pi\pi\pi_s\pi_a) - M(K\pi\pi\pi\pi_s)$, was calculated. Fig. 2(a) shows the invariant mass $M(D^{*+}\pi_a) = \Delta M^{\rm ext} + M(D^{*+}_{\rm PDG})$, where

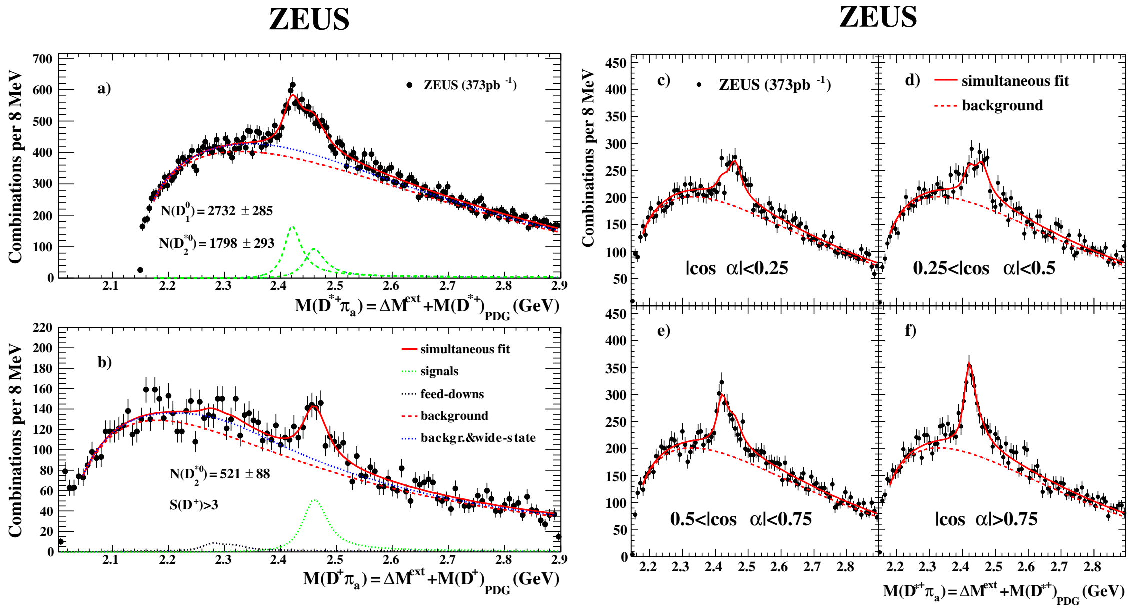


**Figure 2:** *The mass distributions (dots) a) $M(D^{*+}\pi_a)$ and b) $M(D^+\pi_a)$. The solid curves are the result of a simultaneous fit to a) $D_1^0$ and $D_2^{*0}$ and to b) $D_2^{*0}$ and feed-downs plus background function (dashed curves). The contributions of the wide states $D_1(2430)^0$ and $D_0^*(2400)^0$ are given between the dashed and dotted curves. The lowest curves are the contributions of the $D_1^0$ and $D_2^{*0}$ to the fit. The mass distributions (dots) $M(D^{*+}\pi_a)$ in four helicity intervals are shown in: (c) $|\cos\alpha|<0.25$; (d) $0.25<|\cos\alpha|<0.50$; (e) $0.50<|\cos\alpha|<0.75$; (f) $|\cos\alpha|>0.75$.*

$M(D^{*+}_{\rm PDG})$ is the nominal $D^{*+}$ mass [1]. A clear signal in the $D_1^0/D_2^{*0}$ mass region is seen. To distinguish between $D_1^0, D_2^{*0} \to D^{*+}\pi^-$, their $|\cos\alpha|$ distributions were used (see Sec. 1). Fig. 2(c,d,e,f) shows the $M(D^{*+}\pi_a)$ distribution in four $|\cos\alpha|$ bins. From the HQET predictions $h(D_1^0)=3$ and $h(D_2^{*0})=-1$ it is expected that the $D_1^0$ contribution increases and the $D_2^{*0}$ contribution decreases with $|\cos\alpha|$. The distributions in Fig. 2(c,d,e,f) qualitatively confirms these expectations.

The $D_2^{*0}$ was also reconstructed in the decay mode $D_2^{*0} \to D^+\pi^-$ by combining each $D^+$ candidate with an additional track, assumed to be a pion $\pi_a$, with a charge opposite to that of the $D^+$. Fig. 2(b) shows the "extended" mass difference $\Delta M^{\rm ext} = M(K\pi\pi\pi_a) - M(K\pi\pi)$ spectrum with $M(D^+\pi_a) = \Delta M^{\rm ext} + M(D^+_{\rm PDG})$, where $M(D^+_{\rm PDG})$ is the nominal $D^+$ mass [1]. A clear $D_2^{*0}$ signal is seen. No indication of the $D_1^0 \to D^+\pi^-$ decay is seen, as expected from angular momentum and parity conservation for a $J^P=1^+$ state. A small excess of events over background is seen around 2.3GeV in the $D^+\pi^-$ mass distribution. This excess originates from the decay chains $D_1^0, D_2^{*0} \to D^{*+}\pi^-$ with $D^{*+} \to D^+\pi^0$ or $D^{*+} \to D^+\gamma$. Since the available phase space in the $D^{*+} \to D^+\pi^0$ decay is small and $D^+$ is much heavier than $\pi^0$, the energy and momentum of $D^+$ are close to those of $D^{*+}$. Consequently, the enhancements seen in the $M(D^+\pi_a)$ distribution are called **feed-downs** of the excited charm mesons $D_1^0$, $D_2^{*0}$, shifted down approximately by the value of the $\pi^0$ mass. To extract the signals of the excited neutral charm mesons, a $\chi^2$ fit was performed using simultaneously the $M(D^+\pi_a)$ distribution shown in Fig. 2(b) and the $M(D^{*+}\pi_a)$ distributions in Figs. 2(c,d,e,f). For the $D^{*+}\pi_a$ spectra the fit included: the background contribution and the signals of $D_1^0$, $D_2^{*0}$ and $D^0(2430)$ states. For the $D^+\pi_a$ spectrum the fit included: the background contribution, the signals of $D_2^{*0}$ and $D^{*0}(2400)$ states, the $D_1^0$, $D_2^{*0}$ and $D^0(2430)$ feed-downs. Each signal was fitted to a relativistic $D$-wave Breit-Wigner (BW) function [4] convoluted with a Gaussian resolution function. The feed-down fitting procedure is described in Refs. [4, 5].

The fit had a low sensitivity to some parameters. Thus, the masses and widths of known wide states $D^{*0}(2400)$ and $D^0(2430)$ were set to the PDG [1] values and their helicity parameters to the HQET predictions $h(D^{*0}(2400))=0$ and $h(D^0(2430))=0$. As both $D^0(2430)$ and $D_1^0$ mesons are $J^P=1^+$ states, the yield of $D^0(2430)$ was required to be the same as that of $D_1^0$. The $h(D_2^{*0})$ parameter in the fit has been fixed to the HQET prediction $h(D_2^{*0})=-1$. The relative yields of the $D_1^0$, $D_1^0(2430)$, $D_2^{*0}$ feed-down contributions were taken to be equal to those for the signals in the $D^{*+}\pi^-$ decay channel.

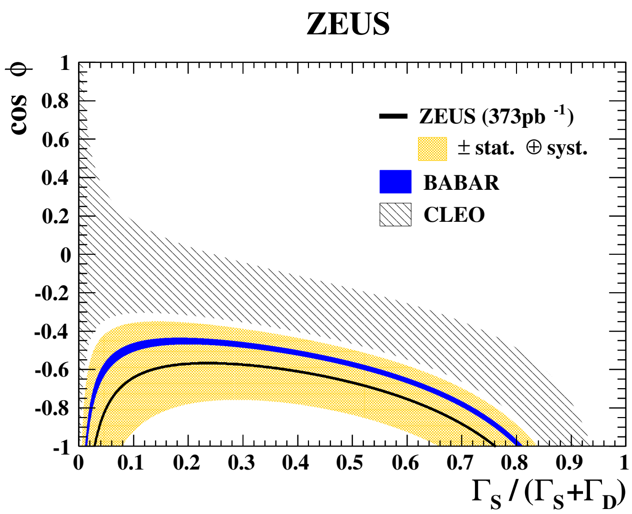


**Figure 3:** *The allowed region of* $\cos\phi$*, where* $\phi$ *is the relative phase of* $S$*- and* $D$*-wave amplitudes, versus the fraction of* $S$*-wave in the* $D_1^0 \to D^*\pi$ *decay for* ZEUS, BABAR *and* CLEO *measurements.*

The measured masses $M(D_1^0)=2423.1\pm1.5^{+0.4}_{-1.0}$MeV and $M(D_2^{*0})=2462.5\pm2.4^{+1.3}_{-1.1}$MeV [3] are consistent with the results of a previous ZEUS publication [6], latest PDG values $M(D_1^0)=2421.3\pm0.6$MeV, $M(D_2^{*0})=2462.6\pm0.7$MeV [1] and with the BABAR measurements $M(D_1^0)=2423.1\pm1.5^{+0.4}_{-1.0}$MeV and $M(D_2^{*0})=2462.5\pm2.4^{+1.3}_{-1.1}$MeV [7].

The $D_1^0$ width, $\Gamma(D_1^0)=38.8\pm5.0^{+1.9}_{-5.4}$MeV, is consistent with the PDG value [1] of $27.1\pm2.7$MeV and agrees with the BABAR measurement of $31.4\pm0.5\pm1.3$MeV [7]. The $D_2^{*0}$ width, $\Gamma(D_2^{*0}) = 46.6\pm8.1^{+5.9}_{-3.8}$MeV, is consistent with the PDG value [1] of $49.0\pm1.4$MeV, and with the BABAR measurement of $50.5\pm0.6\pm0.7$MeV.

[3] The first uncertainties are statistical and the second are systematical. The later are discussed in details in Refs. [4, 5].

The $D_1^0$ helicity parameter, $h(D_1^0)=7.8^{+6.7+4.6}_{-2.7-1.8}$, is consistent with the BABAR value of $h(D_1^0)=5.72\pm0.25$ and somewhat above HQET prediction of $h=3$ and measurements by CLEO [10] with $h(D_1^0)=2.74^{+1.40}_{-0.93}$. The fit with $h(D_2^{*0})$ as a free parameter yielded similar results for all other free parameters with larger errors and with $h(D_2^{*0})=-1.16\pm0.35$, in agreement with the HQET prediction of $h=-1$. The range of the measured $h(D_1^0)$ restricted to one standard deviation is shown in Fig. 3 in a plot of $\cos\phi$ versus $r$. A similar measurement by BELLE [11] is consistent with a pure $D$-wave, i.e. $\Gamma_S/(\Gamma_S+\Gamma_D)=0$.

## 4. $D_1(2420)^+$ and $D_2^*(2460)^+$ reconstruction

For the reconstruction of charged excited mesons each $D^0$ candidate was combined with an additional track, assumed to be a pion ($\pi_a$), with either positive or negative charge. For each excited-charm-meson candidate, the "extended" mass difference $\Delta M^{\rm ext}=M(K\pi\pi_a)-M(K\pi)$ was calculated.

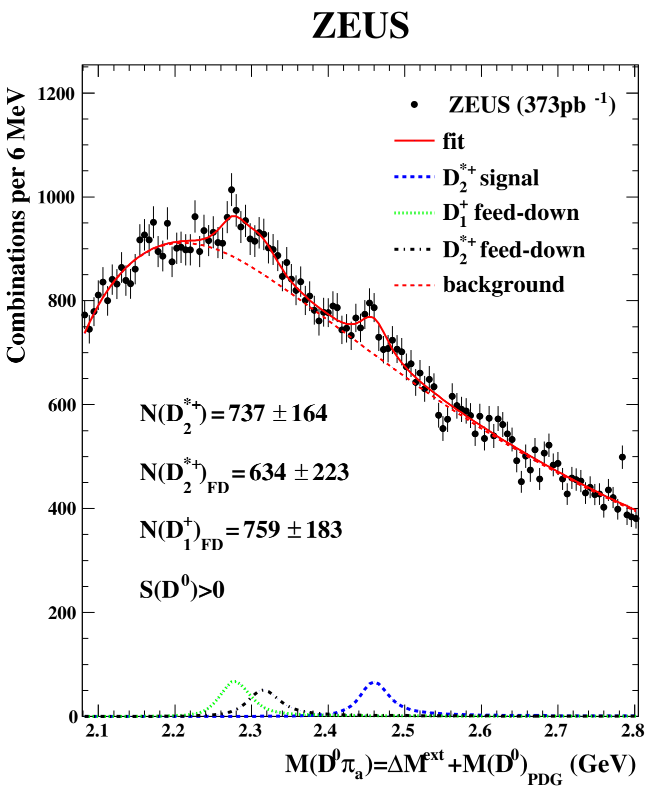


**Figure 4:** *The mass distribution (dots) $M(D^0\pi_a)$. The solid curve is the result of a simultaneous fit to the feed-down (FD) $D_1^+$ and $D_2^{*+}$ contributions and to the $D_2^{*+}$ signal plus background function (dashed curves). The lowest curves are the contributions of the $D_1^+$ and $D_2^{*+}$ to the fit.*

Fig. 4 shows the invariant mass $M(D^0\pi_a)=\Delta M^{\rm ext}+M(D^0_{\rm PDG})$, where $M(D^0_{\rm PDG})$ is the nominal $D^0$ mass [1]. A clear signal of $D_2^{*+}\to D^0\pi^+$ is seen. An enhancement above background is also seen at the mass region around 2.3GeV. It is a sum of feed-downs of $D_1^+$ and $D_2^{*+}$ states, which originates from the decay chains $D_1^+,D_2^{*+}\to D^{*0}\pi^+$ with $D^{*0}\to D^0\pi^0$ or $D^{*0}\to D^0\gamma$. To extract the signals of the charged excited charm mesons, a $\chi^2$ fit was performed using the $M(D^0\pi_a)$ distribution shown in Fig. 4. The fit included: the background contribution, the signal of $D_2^{*+}$ and the feed-downs of the $D_1^+$ and $D_2^{*+}$ states. The $D_2^{*+}$ signal was fitted to relativistic Breit-Wigner distributions convoluted with the appropriate resolution function. The widths $\Gamma(D_2^{*+})$ and $\Gamma(D_1^+)$ were set to the PDG values and the helicity parameters to the HQET predictions $h(D_2^{*+})=-1$, $h(D_1^+)=3$. The feed-down shapes were modelled as described in Refs. [4, 5]. The masses, widths and helicity parameters of the feed-downs were the same as for the signal. The measured masses

$M(D_1^+)$=2421.9±4.7$^{+3.4}_{-1.2}$MeV and $M(D_2^{*+})$=2460.6±4.4$^{+3.6}_{-0.8}$MeV agree with the average values from PDG [1] $M(D_1^+)$=2423.4±3.1MeV and $M(D_2^{*+})$=2464.4±2.9MeV and with other measurements.

## 5. Excited charm meson fragmentation fractions and branching ratios

In addition to the mass spectra and decay properties, fragmentation fractions for the $D_1$ and $D_2^*$ mesons were measured in this analysis. The measured fragmentation fractions $f(c\to D_1^0)$=2.9±0.5$^{+0.5}_{-0.5}$% and $f(c\to D_2^{*0})$=3.9±0.9$^{+0.8}_{-0.6}$% were found to be consistent with those obtained in $e^+e^-$ annihilations [12, 13] and previous ZEUS results [6]. This analysis presents the first measurement of $f(c\to D_1^+)$=4.6±1.8$^{+2.0}_{-0.3}$% and $f(c\to D_2^{*+})$=3.2±0.8$^{+0.5}_{-0.2}$%. The sums of the fragmentation fractions, $f(c\to D_1^0)+f(c\to D_2^{*0})$=6.8±1.0$^{+0.9}_{-0.8}$% and $f(c\to D_1^+)$ + $f(c\to D_2^{*+})$=7.8±2.0$^{+2.0}_{-0.4}$% agree with the predictions of the tunnelling model of 8.5% [14]. The ratios $f(c\to D_1^0)/f(c\to D_2^{*0})$=0.8±0.2±0.2 and $f(c\to D_1^+)/f(c\to D_2^{*+})$=1.4±0.7$^{+0.7}_{-0.1}$ are in agreement with the simple spin-counting prediction of 3/5. The measured value $\mathcal{B}_{D_2^{*0}\to D^+\pi^-}/\mathcal{B}_{D_2^{*0}\to D^{*+}\pi^-}$=1.4±0.3$^{+0.3}_{-0.3}$ is lower than most other measurements, including the previous ZEUS measurement [6] 2.8±0.8$^{+0.5}_{-0.6}$. However, the measured value is in agreement with the precise measurements of BABAR [7] 1.47±0.03±0.16, which constrains the PDG average of 1.56±0.16 [1]. The measured value $\mathcal{B}_{D_2^{*+}\to D^0\pi^+}/\mathcal{B}_{D_2^{*+}\to D^{*0}\pi^+}$=1.1±0.4$^{+0.3}_{-0.2}$ is slightly lower, but still consistent with the measurement of BABAR [15] 1.63$^{+0.14+0.22}_{-0.12-0.19}$. However, the measurement of BABAR is not taken into account in the PDG average, which relies only on the imprecise CLEO [16] result 1.9±1.1±0.3. Thus, the measurement presented in this analysis, if taken into account, can significantly improve the accuracy of the PDG average.

Theoretical models (see Refs. [4, 5] for a more detailed overview) predict the ratios $\mathcal{B}_{D_2^{*0}\to D^+\pi^-}/\mathcal{B}_{D_2^{*0}\to D^{*+}\pi^-}$ and $\mathcal{B}_{D_2^{*+}\to D^0\pi^+}/\mathcal{B}_{D_2^{*+}\to D^{*0}\pi^+}$ to be in the range from 2.3 to 3, well above the values measured in this analysis. Those discrepancies can be explained with a low precision of the experimental data used for those predictions (i.e. masses and widths).

## 6. Conclusions

In this analysis, the production of excited charm mesons at HERA and their properties were studied. The full available data taken by the ZEUS experiment from 2003 to 2007 has been used. Signals of $D_1^0$ and $D_2^{*0}$ were seen in the $D^{*+}\pi^-$ decay mode and a clear $D_2^{*0}$ signal was seen in the $D^+\pi^-$ decay mode. The study of excited charm meson properties was concentrated on spectroscopy including mass, width and helicity measurements and the measurement of fragmentation fractions and branching ratios. The measured $D_1^0$ and $D_2^{*0}$ masses and widths are in good agreement with the latest PDG values. The measured $D_1^0$ helicity parameter allows for some $S$-wave mixing in its decay to $D^{*+}\pi^-$. The result is also consistent with a pure $D$-wave hypothesis. The helicity of $D_2^{*0}$, when set free in the fit, is consistent with the HQET prediction, $h$=−1. A clear $D_2^{*+}$ signal is seen for the first time at HERA in the $D^{*0}\pi^+$ decay mode. Feed-downs of both resonances $D_1^+$ and $D_2^{*+}$ in the decay mode $D^{*0}\pi^+$ are seen in the expected mass region of $M(D^0\pi^+)\approx$2.3GeV. To measure the mass parameters from the latter a special procedure has been developed. The measured $D_1^+$ and $D_2^{*+}$ masses are in good agreement with the



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PDG values and the $D_2^{*+}$ mass is consistent with the precise measurements of BABAR. The fractions of $c$-quarks hadronising into $D_1^0$ and $D_2^{*0}$ are consistent with those from the previous ZEUS publication and, in comparison with $e^+e^-$ annihilation results, in agreement with charm fragmentation universality. The fractions of $c$-quarks hadronising into $D_1^+$ and $D_2^{*+}$ were measured for the first time and are consistent, respectively, with the fractions of the neutral charm excited states $D_1^0$ and $D_2^{*0}$. The ratios of the $D_2^{*0}$ and $D_2^{*+}$ dominant branching ratios are consistent with the PDG values.

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