PRODUCTION OF EXCITED P-WAVE CHARM MESONS AT HERA

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ON BEHALF OF THE ZEUS COLLABORATION

The production of excited charm mesons has been observed with the ZEUS detector at HERA. Neutral orbitally excited P-wave charm mesons have been reconstructed in the $D^{*\pm}\pi^{\mp}$ final state and the charm-strange meson $D^{\pm}_{s1}(2536)$ was found in the $D^{*\pm}K^0_s$ final state. The fraction of $D^{*\pm}$ mesons originating from the decays of these mesons has been calculated and converted to the rate of c quarks hadronising as the excited charm mesons. A search for radially excited charm mesons in the $D^{*\pm}\pi^+\pi^-$ final state has also been performed. The results are compared with those obtained in e^+e^- annihilations.

1 Introduction

P-wave charm states (orbital angular momentum L=1 of the $c\bar{q}$ system) are expected in addition to the L=0 D and D^* mesons. These P-wave mesons appear as singlet or triplet states and can decay to L=0 states plus a π or a K [1]. Heavy Quark Effective Theory [2] predicts that the four states appear in two doublets with total angular momentum j=L+s=3/2 (narrow states) or 1/2 (broad states), where s is the spin of the light quark. Narrow excited charm mesons, $D_1(2420)$ and $D^*_2(2460)$, were observed in the $D^*\pi$ decay mode and identified as members of the j=3/2 doublet with spin-parity $J^P = 1^+$ and 2^+, respectively [1]. A charm-strange excited meson, $D^{\pm}_{s1}(2536)$, was found in the $D^{*\pm}K^0_s$ final state [1].

Radially excited charm mesons with mass about 2.6 GeV are predicted [3] to decay into $D\pi\pi$ or $D^*\pi\pi$. A narrow resonance in the $D^{*\pm}\pi^+\pi^-$ final state at 2.637 GeV, interpreted as the radially excited $D^{*'\pm}$, was reported by DELPHI [4]. No evidence for this state has been found by OPAL and CLEO [5].

We report on orbitally excited charm-meson production and a search for radially excited charm states in e-p collisions. The analysis was performed with ZEUS 1995-2000 data, when HERA collided 27.5 GeV positrons or electrons with 820 GeV (1995-1997) or 920 GeV (1998-2000) protons. Events from photoproduction and deep inelastic scattering were selected with a three-level trigger and used for these analyses.

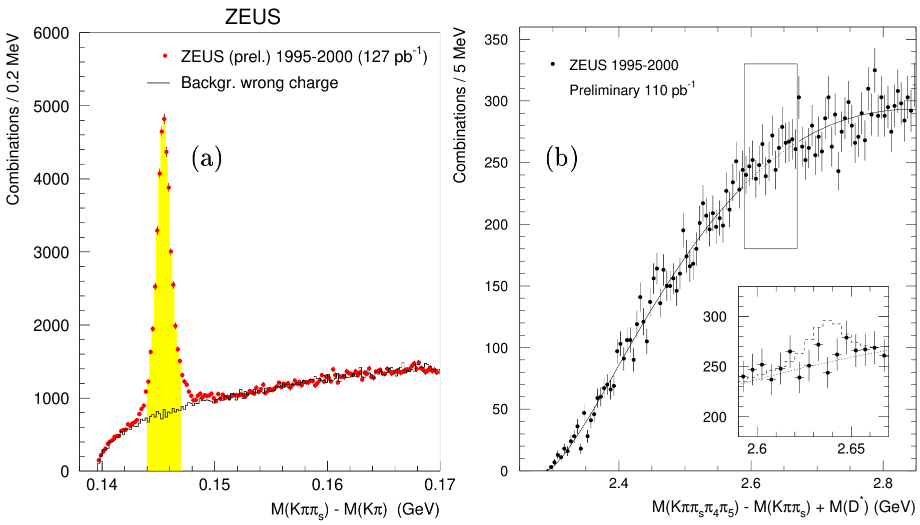

Figure 1. (a) $M(K\pi\pi_S) - M(K\pi)$ distribution in the D^0 mass region (full dots). The histogram is the distribution for wrong charge combinations. (b) $M(K\pi\pi_S\pi_4\pi_5) - M(K\pi\pi_S) + M(D^*)$ for $D^{*'\pm}$ candidates. The rectangle is the $D^{*'\pm}$ signal window. Dashed histogram in inset is Monte Carlo $D^{*'\pm}$ signal normalised to the obtained upper limit and added to the fit interpolation (dotted curve) in the signal window.

2 $D_1^0(2420)$ and $D_2^{*0}(2460)$ production

D_1^0 and D_2^{*0} mesons were reconstructed [6] via their decays to $D^{*\pm}\pi^{\mp}$ followed by the $D^{*\pm}$ decays, $D^{*+} \to D^0\pi_S^+ \to (K^-\pi^+)\pi_S^+(+c.c.)$, where π_S is the soft pion from the $D^{*\pm}$ decay. Fig. 1a shows the mass difference distribution, $\Delta M = M(K\pi\pi_S) - M(K\pi)$, in the D^0 mass region $1.83 < M(K\pi) < 1.90$ GeV with transverse momenta $p_\perp(K,\pi) > 0.5$ GeV and $p_\perp(\pi_S) > 0.125$ GeV in the kinematic range $p_\perp^{D^*} > 2$ GeV and $-1.5 < \eta^{D^*} < 1.5$, where $\eta = -\ln\tan(\theta/2)$ is the pseudorapidity and the polar angle θ is defined with respect to the proton beam direction. A clear $D^{*\pm}$ signal is seen (dots) on top of a small combinatorial background, estimated by wrong charge combinations (histogram) where both D^0 tracks have the same charge and π_S has the opposite charge. $D^{*\pm}$ candidates with $0.144 < \Delta M < 0.147$ GeV were kept for the excited charm meson reconstruction. A signal of 31350 ± 240 $D^{*\pm}$

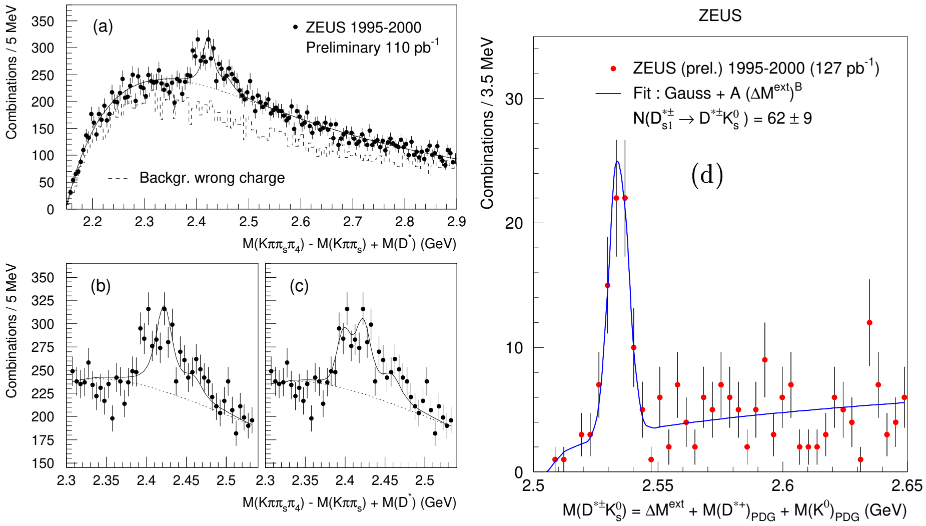

Figure 2. (a-c) Extended mass difference distribution for $D^{*\pm}$ candidates (full dots). Dashed histogram is for wrong charge cominations. The curves are the results of unbinned likelihood fits. In (a) and (b) the solid curves are fits to background parametrisation and two Breit-Wigner distributions convoluted with a Gaussian function. In (c) an additional Gaussian-shaped resonance near 2.4 GeV is assumed in the fit. Dotted curves are fitted shapes of the combinatorial background. (d) Effective $M(D^{*\pm}K_S^0)$ distribution (full dots). Solid line is a fit to a Gaussian resonance plus a background of the form $A(\Delta M^{ext})^B$.

mesons was found in this range after background subtraction.

A neutral excited charm-meson candidate was formed by combining a $D^{*\pm}$ candidate with another pion (π_4) with charge opposite to that of the $D^{*\pm}$ and $p_\perp(\pi_4) > 0.3$ GeV. Figure 2a shows the "extended" mass difference distribution, $M(K\pi\pi_S\pi_4) - M(K\pi\pi_S) + M(D^*)$, where $M(D^*)$ is the nominal $D^{*\pm}$ mass [1] (full dots). A clear excess is seen around $2.4 - 2.5$ GeV, where contributions from $D_1^0(2420)$ and $D_2^{*0}(2460)$ mesons are expected. No excess is seen for wrong charge combinations (dashed histogram), where $D^{*\pm}$ and π_4 have the same charges.

The solid curves in Figs. 2a and 2b result from a unbinned likelihood fit to two Breit-Wigner shapes with masses and widths fixed to the nominal D_1^0 and D_2^{*0} values [1], convoluted with a Gaussian function and multiplied by helicity spectrum functions for $J^P = 1^+$ and 2^+ states, respectively. The background shape was parametrised by the form $x^\alpha \cdot exp(-\beta \cdot x + \gamma \cdot x^2)$, where $x = M(K\pi\pi_S\pi_4) - M(K\pi\pi_S) - M(\pi)$. The fitted curve describes the distribution reasonably well in the whole range, except for a narrow enhancement near 2.4 GeV. In Fig. 2c a similar fit is performed with an additional Gaussian-shaped resonance with free mass and width. The fit yielded 211 ± 49 entries for the narrow enhancement with mass value $2398.1 \pm 2.1\,(\mathrm{stat.})^{+1.6}_{-0.8}\,(\mathrm{syst.})$ MeV. The width was consistent with the expected resolution. The enhancement may indicate a new excited charm meson, a result of an interference effect or a statistical fluctuation. The number of reconstructed D_1^0 and D_2^{*0} mesons in the 3-resonance fit are 526 ± 65 and 203 ± 60, respectively.

The acceptance-corrected fractions of $D^{*\pm}$ mesons originating from D_1^0 and D_2^{*0} in the measured kinematic range were found to be $R_{D_1^0 \to D^{*\pm}\pi^\mp/D^{*\pm}} = 3.40 \pm 0.42\,(\mathrm{stat.})^{+0.78}_{-0.63}\,(\mathrm{syst.})\%$ and $R_{D_2^{*0} \to D^{*\pm}\pi^\mp/D^{*\pm}} = 1.37 \pm 0.40\,(\mathrm{stat.})^{+0.96}_{-0.33}\,(\mathrm{syst.})\%$. Extrapolating to the full kinematic phase space by a Monte Carlo (MC) simulation and using the measured partial width ratio, $\Gamma(D_2^{*0} \to D^+\pi^-)/\Gamma(D_2^{*0} \to D^{*+}\pi^-) = 2.3 \pm 0.6$, the rate of c quarks hadronising as D^{*+} mesons, $f(c \to D^{*+}) = 0.235 \pm 0.007 \pm 0.007$, and isospin conservation, the above fractions can be converted to the rates of c quarks hadronising as D_1^0 and D_2^{*0} mesons. We obtain: $f(c \to D_1^0) = 1.46 \pm 0.18\,(\mathrm{stat.})^{+0.33}_{-0.27}\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{ext.})\%$ and $f(c \to D_2^{*0}) = 2.00 \pm 0.58\,(\mathrm{stat.})^{+1.40}_{-0.48}\,(\mathrm{syst.}) \pm 0.41\,(\mathrm{ext.})\%$, where the third errors are uncertainties in $f(c \to D^{*+})$ and the $D_2^{*0} \to D^{*+}\pi^-$ branching ratio. These rates are consistent with e^+e^- rates for these resonances as measured, for example, by the CLEO Collaboration [7]: $f(c \to D_1^0) = 1.8 \pm 0.3\%$ and $f(c \to D_2^{*0}) = 1.9 \pm 0.3\%$.

3 Search for radially excited $D^{*'\pm}$

$D^{*'\pm}$ candidates were reconstructed [6] from their decays to $D^{*\pm}\pi^+\pi^-$ by combining the $D^{*\pm}$ candidates in the decay mode of Section 2 with two tracks, assumed to be pions (π_4 and π_5) with opposite charges and $p_\perp > 0.125$ GeV. Fig. 1b shows the distribution of the extended mass difference $M(K\pi\pi_S\pi_4\pi_5) - M(K\pi\pi_S) + M(D^*)$. No narrow resonance is seen. An upper limit on the fraction of $D^{*\pm}$ mesons originating from $D^{*'\pm}$ decays is given within a signal window $2.59 < M(D^{*'\pm}) < 2.67$ GeV, which covers theoretical predictions [3] and the DELPHI measurement [4]. The background distribution was fitted outside the signal region to $x^\alpha \cdot exp(-\beta \cdot x)$, where $x = M(K\pi\pi_S\pi_4\pi_5) - M(K\pi\pi_S) - 2M(\pi)$. The number of reconstructed $D^{*'\pm}$ mesons, 91 ± 75, was obtained by subtracting the background function, integrated over the signal mass window, from the observed number of candidates in the window. After dividing by the number of $D^{*\pm}$ and correcting for acceptance, an upper limit of $R_{D^{*'+} \to D^{*+}\pi^+\pi^- / D^{*+}} < 2.3\%$ (95% $C.L.$) is obtained in the measured kinematic region. Extrapolating by a MC simulation to the full kinematic phase space and using the known $f(c \to D^*)$ value, we obtain a $D^{*'\pm}$ production limit of $f(c \to D^{*'+}) \cdot B_{D^{*'+} \to D^{*+}\pi^+\pi^-} < 0.7\%$ (95% $C.L.$) compared to 0.9% as reported by OPAL [8]

4 Production of the charm-strange meson $D_{s1}^{\pm}(2536)$

$D_{s1}^{\pm}$ mesons were reconstructed [9] via their decays to $D^{*\pm}K_S^0$ with $K_S^0 \to \pi^+\pi^-$. K_S^0 candidates were identified by using all pairs of oppositely charged tracks with $p_\perp > 0.2\,\mathrm{GeV}$. Secondary vertices were found by calculating intersection points in the plane perpendicular to the beams. Assuming the two K_S^0 tracks to be pions (π_3 and π_4), the invariant mass, $M(\pi_3\pi_4)$, was calculated for each selected K_S^0 candidate. A clean K_S^0 signal was extracted after applying standard cuts of a $V0$-finding package [9]. Only K_S^0 candidates with $0.480 < M(\pi_3\pi_4) < 0.515\,\mathrm{GeV}$ were kept for the $D_{s1}^{\pm}$ reconstruction. For each $D_{s1}^{\pm}$ candidate, the extended mass difference, $\Delta M^{ext} = M(K\pi\pi_S\pi_3\pi_4) - M(K\pi\pi_S) - M(\pi_3\pi_4)$, was calculated. Fig. 2d shows the effective $M(D^{*\pm}K_S^0)$ distribution in terms of $\Delta M^{ext} + M(D^{*+})_{PDG} + M(K^0)_{PDG}$ (solid dots), where $M(D^{*+})_{PDG}$ and $M(K^0)_{PDG}$ are the nominal $D^{*\pm}$ and K^0 masses [1]. A clear signal is seen at the value of $M(D_{s1}^{\pm})$. The solid curve is a unbinned likelihood fit to a Gaussian resonance plus a background of the form $A(\Delta M^{ext})^B$. The fit yielded 62.3 ± 9.3 $D_{s1}^{\pm}$ mesons. The mass value was found to be $M(D_{s1}^{\pm}) = 2534.2 \pm 0.6 \pm 0.5\,\mathrm{MeV}$, in rough agreement with the PDG value [1]. The last error is due to the uncertainty in $M(D^{*+})_{PDG}$.

The angular distribution of the D_{s1} signal was studied via the helicity angle, α, defined as the angle between the K_S^0 and π_S momenta in the $D^{*\pm}$ rest frame. The distribution $dN/d\cos\alpha$ was fitted to $(1 + R\cos^2\alpha)$. The unbinned likelihood fit yielded $R = -0.53 \pm 0.32\,(\mathrm{stat.})^{+0.05}_{-0.14}\,(\mathrm{syst.})$, consistent with the CLEO value [10] $R = -0.23^{+0.40}_{-0.32}$. Both measurements are consistent with $R = 0$, i.e. $J^P = 1^+$ for the D_{s1} meson. However, our result is not inconsistent with $R = -1$, i.e. $J^P = 1^-$ or 2^+ [11].

The fraction of $D^{*\pm}$ mesons originating from $D_{s1}^{\pm}$ mesons in the measured kinematic region is: $R_{D_{s1}^{\pm} \to D^{*\pm}K^0/D^{*\pm}} = 1.77 \pm 0.26\,(\mathrm{stat.})^{+0.11}_{-0.09}\,(\mathrm{syst.})\%$. Converting to the rate of c quarks hadronising as D_{s1}^{+} mesons and extrapolating by a MC simulation to the full kinematic phase space, we obtain: $f(c \to D_{s1}^{+}) = 1.24 \pm 0.18\,(\mathrm{stat.})^{+0.08}_{-0.06}\,(\mathrm{syst.}) \pm 0.14\,(\mathrm{br.})\%$. The third error is due to uncertainties in $f(c \to D^{*+})$ and the $D_{s1}^{+} \to D^{*+}K^0$ branching ratio. The rate agrees with the OPAL value [12] of $1.6 \pm 0.4 \pm 0.3\%$. This rate is about twice that expected, assuming $f(c \to D_1^0) \approx 2\%$ [6] and $\gamma_s \approx 0.3$ [13], where γ_s is the strangeness suppression factor in charm production.

5 Summary

Significant production of the excited P-wave charm mesons $D_1^0(2420)$, $D_2^{*0}(2460)$ and $D_{s1}^{\pm}(2536)$ has been observed in e-p collisions at HERA. The fractions of $D^{*\pm}$ mesons in a restricted kinematic region originating from these states were measured and converted to rates of c quarks hadronising as these mesons. The rates agree with previous e^+e^- measurements. The rate for $D_{s1}^{\pm}$ is about twice that expected from the D_1^0 rate and a strangeness suppression factor of ≈ 0.3. A narrow mass enhancement at around 2.4 GeV was seen in the $D^{*\pm}\pi^{\mp}$ final state, which may indicate a new excited meson, an interference effect or a statistical fulctuation. No significant production of the radially excited meson $D^{*'\pm}$ seen by DELPHI was observed and the upper limit on its production is consistent with the OPAL e^+e^- measurement.

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