Resonance Searches at HERA

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Inclusive production of $K^0_SK^0_S$ in ep collisions was studied with the ZEUS detector. Significant production of $J^{PC} = 2^{++}$ tensor mesons and of the $0^{++}$ glueball candidate $f_0(1710)$ was seen. Masses and widths were compared with previous experiments. The H1 Collaboration saw a charm pentaquark candidate in the $D^*p$ spectrum at 3.1 GeV, which was not confirmed by a ZEUS higher statistics search. With the full HERA statistics, H1 did not see a signal in this region. Masses, widths and helicity parameters of excited charm and charm-strange mesons were measured by ZEUS. Rates of $c$ quarks hadronising into these mesons were determined and a search for a radially excited charm meson was performed.

1 Introduction

The HERA ep collider operated with electrons or positrons at 27.6 GeV and protons at 820 or 920 GeV. Each of the two general purpose experiments H1 and ZEUS collected during 1995 - 2000 ("HERA I") $\approx 120 \, pb^{-1}$ and during 2003 - 2007 ("HERA II") $\approx 370 \, pb^{-1}$. Two kinematic regions have been explored: Deep inelastic scattering (DIS) with photon virtuality $Q^2 > 1 \, GeV^2$, where the scattered electron is visible in the main detector and photoproduction (PHP) with $Q^2 < 3 \cdot 10^{-4} \, GeV^2$, where the virtual photon radiated from the incoming electron is quasi-real. The sample is dominated by PHP events.

2 Glueball search in the $K^0_SK^0_S$ system

Glueballs are predicted by QCD. The lightest glueball is expected to have $J^{PC} = 0^{++}$ and a mass in the range 1550-1750 MeV and can mix with $qq$ scalar meson nonet $I=0$ states of similar mass. There are four such established states: $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$, but only two can fit into the nonet. The $f_0(1710)$ state is considered as a possible glueball candidate. The $K^0_SK^0_S$ system can couple to $J^{PC} = 0^{++}$ and $2^{++}$. Therefore, it is a good place to search for the lowest lying $0^{++}$ glueball.

2.1 Previous results

The $e^+e^-$ experiments TASSO and L3 studied the exclusive reaction $\gamma\gamma \rightarrow K^0_SK^0_S$. L3 saw 3 peaks and attributed them to $f_2(1270)/a_2(1320)$, $f_2^*(1525)$ and $f_0(1710)$. A maximum likelihood fit with 3 Breit-Wigner (BW) functions plus background yielded $f_2^*(1525)$ mass and width values consistent with the Particle Data Group (PDG) and a 4 standard deviation

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(s.d.) signal for $f_0(1710)$ with mass and width values above PDG. The TASSO \cite{3} $K_S^0K_S^0$ spectra had no $f_2(1270)/a_2(1320)$ signal and a sizable $f'_2(1525)$ enhancement. The result was interpreted by interference effects between the 3 $J^P = 2^+$ resonances $f_2(1270)$, $a_2(1320)$ and $f'_2(1525)$ and the spectra was fitted as a sum of 3 coherent BW functions. Based on SU(3) symmetry arguments \cite{4}, the sign of the $a_2(1320)$ term for $K_S^0K_S^0$ is negative and the coefficients of the $f_2(1270)$, $a_2(1320)$ and $f'_2(1525)$ BW amplitudes are $+5$, $-3$ and $+2$, respectively.

2.2 This analysis

The reaction $e^+p \rightarrow K_S^0K_S^0 + X$ was studied \cite{3} with the full HERA luminosity of 0.5 fb$^{-1}$. Both PHP and DIS events were included. No explicit trigger requirement was applied for selecting the above reaction.

$K_S^0$ mesons were identified via their decay mode $K_S^0 \rightarrow \pi^+\pi^-$. A clean $K_S^0$ signal was seen for events with $\geq 2K_S^0$ candidates. The number of $K_S^0K_S^0$ pairs found in the $K_S^0$ mass range $481 < M(\pi^+\pi^-) < 515$ MeV is $\approx 672,000$.

Figure 1 shows the $K_S^0K_S^0$ mass distribution reconstructed by combining two $K_S^0$ candidates selected in the above mass window. Three peaks are seen around 1.3, 1.5 and 1.7 GeV. No state heavier than 1.7 GeV was observed. The invariant-mass spectrum, $m$, was fitted as a sum of relativistic Breit-Wigner (RBW) resonances and a smoothly varying background $U(m) = m^2 \exp(-Bm)$, where $A$ and $B$ are free parameters.

Two types of fit, as performed for the reaction $\gamma\gamma \rightarrow K_S^0K_S^0$ by L3 \cite{2} and TASSO \cite{3}, respectively, were tried. The first fit (not shown) is an incoherent sum of three modified RBW resonances, $R$, of the form $F(m) = CR\frac{M_R^2}{M_R^2-m^2-iM_R\Gamma_R}$, representing the peaks $f_2(1270)/a_2(1320)$, $f'_2(1525)$ and $f_0(1710)$. Here $C_R$ is the resonance amplitude and $M_R$ and $\Gamma_R$ are the resonance mass and width, respectively. The goodness of this fit is reasonable ($\chi^2/ndf = 96/95$); however, the dip between the $f_2(1270)/a_2(1320)$ and $f'_2(1525)$ is not well reproduced.

Figure 1 shows a coherent fit motivated by SU(3) predictions \cite{4}. Each resonance amplitude, $R$, is described by the RBW form \cite{3} $BW(R) = \frac{M_R^2}{M_R^2-m^2-iM_R\Gamma_R}$. The decays of the tensor ($J^P = 2^+$) mesons $f_2(1270)$, $a_2^0(1320)$ and $f'_2(1525)$ into the two pseudoscalar ($J^P = 0^+$) mesons $K^0\bar{K}^0$ are related by SU(3) symmetry with a specific interference pattern. The intensity is the modulus-squared of the sum of these 3 amplitudes plus the incoherent addition of $f_0(1710)$ and a non-resonant background.

Assuming SU(3) symmetry and a direct coupling of the $2^+$ states to the exchanged photon, the fitted function to the $m(K_S^0K_S^0)$ spectra is given by $F(m) = a[5 \cdot BW(f_2(1270)) - 3 \cdot BW(a_2(1320)) + 2 \cdot BW(f'_2(1525))]^2 + b[BW(f_0(1710))]^2 + c \cdot U(m)$, where $a,b,c$ as well as the

![Figure 1: (a)The $K_S^0K_S^0$ distribution (dots). Solid line is the coherent fit (see text); background function is given by the dashed line. (b)Background-subtracted $K_S^0K_S^0$ distribution (dots); solid line is the fit result.](image-url)
The masses and widths obtained from both fits are shown in Table 1 and compared to PDG [1]. The no-interference fit yields a narrow width for the combined \(f_2(1270)/a_2(1320)\) peak, as was also seen by L3 [2]. The fit with interference yields widths close to the PDG values for all observed resonances. The \(a_2^0(1320)\) mass is below the PDG value. The \(f_2^0(1525)\) and \(f_0(1710)\) masses are somewhat below PDG with uncertainties comparable with the PDG ones. A fit without \(f_0(1710)\) is strongly disfavoured with \(\chi^2/\text{ndf} = 162/97\).

### Table 1: Fitted masses and widths for \(f_2(1270), a_2^0(1320), f_2(1525)\) and \(f_0(1710)\) from the incoherent and coherent fits compared to PDG. The first error is statistical. For \(f_2(1525), f_0(1710)\) the second errors are systematic uncertainties.

| Fit          | No interference | Interference | PDG 2007 Values |
|--------------|-----------------|--------------|-----------------|
| \(\chi^2/\text{ndf}\) in MeV | Mass Width | Mass Width | Mass Width |
| \(f_2(1270)\) | 1304 ± 6 61 ± 11 | 1268 ± 10 176 ± 17 | 1275.4 ± 1.1 185.2 ± 2.5 |
| \(a_2^0(1320)\) | 1523 ± 3 71 ± 5 | 1512 ± 3 83 ± 9 | 1525 ± 5 73 ± 3 |
| \(f_0(1710)\) | 1692 ± 6 125 ± 12 | 1701 ± 5 100 ± 24 | 1724 ± 7 137 ± 8 |

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### 3 Charm pentaquark search in the \(D^*p\) system

A narrow exotic baryon with strangeness +1 around 1530 MeV decaying into \(K^+n\) or \(K^0p\) was seen by various experiments and attributed to the \(\Theta^+ = uudd\bar{s}\) pentaquark state predicted by Diakonov et al. [6]. If a strange pentaquark exists, charmed pentaquarks, \(\Theta_c^0 = uuddc\), could also exist. If \(M(\Theta_c^0) > M(D^*) + M(p) = 2948\) MeV, it can decay to \(D^{\pm}\pi^\mp\).

The H1 Collaboration saw [7] in a DIS HERA I sample of \(\approx 3400\) \(D^* \rightarrow D^0\pi^\pm \rightarrow K^+\pi^\pm\pi^\mp\) a narrow signal of 50.6 ± 11.2 events in the \(D^\mp p\) invariant mass at 3.1 GeV (Fig. 2) with a
width consistent with the mass resolution and a rate of $\approx 1\%$ of the visible $D^*$ production.

ZEUS searched for a $\Theta^0_c$ signal in the $D^{*+}p\bar{p}$ mode with the full HERA I PHP + DIS data sample [8]. Clean $D^{*+}$ signals were seen in the $\Delta M = M(D^{*+}) - M(D^0)$ plots. Two $D^{*+} \rightarrow D^0\pi_S^+$ decay channels were used with $D^0 \rightarrow K^\mp\pi^\pm$ and $D^0 \rightarrow K^\mp\pi^\pm\pi^0\pi^-$. The $\Theta^0_c$ search was performed in the kinematic range $|\eta(D^*)| < 1.6$ and $p_T(D^*) > 1.35(2.8)$ GeV and with $\Delta M$ values between $0.144 - 0.147$ (0.1445 - 0.1465) GeV for the $K\pi\pi$ ($K\pi\pi\pi\pi$) channel. In these bands $\approx 62000$ $D^*$'s were obtained after subtracting wrong-charge combinations with charge $\pm 2$ for the $D^0$ candidate and $\pm 1$ for the $D^*$ candidate. Selecting DIS events with $Q^2 > 1$ GeV$^2$ yielded smaller, but cleaner $D^*$ signals with $\approx 13500$ $D^*$'s.

Protons were selected with momentum $P(p) > 0.15$ GeV. To reduce the pion and kaon background, a parameterisation of the expected $dE/dx$ as a function of $p/m$ was obtained using tagged protons from $\Lambda$ decays and tagged pions from $K_S^0$ decays. The $\chi^2$ probability of the proton hypothesis was required to be above 0.15.

Figure 3 shows the $M(D^{*+}p\bar{p})$ distributions for the $D^0 \rightarrow K\pi$ (left) and $D^0 \rightarrow K\pi\pi\pi$ (right) channels for the full (up) and the DIS (down) samples. No narrow signal is seen in any of the distributions, 95% C.L. upper limits on the fraction of $D^*$ mesons originating from $\Theta^0_c$ decays, $R(\Theta^0_c \rightarrow D^*p/D^*)$, were calculated in a signal window $3.07 < M(D^*) < 3.13$ GeV for the $K\pi\pi$ and $K\pi\pi\pi\pi$ channels. The $M(D^*)$ distributions were fitted to the form $x^ae^{-bx+x^2}$, where $x = M(D^*) - M(D^*) - m_p(PDG)$. The number of reconstructed $\Theta^0_c$ baryons was estimated by subtracting the background function from the observed number of events in the signal window, yielding $R(\Theta^0_c \rightarrow D^*p/D^*) < 0.23\%$ and $< 0.35\%$ for the full and DIS combined two channels. A visible rate of $1\%$ for this fraction is excluded by 9 s.d. (5 s.d.) for the full (DIS) combined sample. The acceptance-corrected rates are, respectively, 0.37% and 0.51%. The 95% C.L. upper limit on the fraction of charm quarks fragmenting to $\Theta^0_c$ times the branching ratio $\Theta^0_c \rightarrow D^*p$ for the combined two channels is $f(c \rightarrow \Theta^0_c) \cdot B_{\Theta^0_c \rightarrow D^*p} < 0.16\% (< 0.19\%)$ for the full (DIS) sample.

In a HERA II DIS data sample that is $\approx 4$ times larger than the HERA I sample, H1 does not see any significant peak at 3.1 GeV (Fig 4). A preliminary 95% C.L. for the ratio of $D^*p$ to $D^*$ is 0.1%.

4 Excited charm and charm-strange mesons

The large charm production at HERA allows to search for excited charm states. ZEUS studied the orbitally excited states $D_1(2420)^0 \rightarrow D^{*+}\pi^- (J^P = 1^+)$, $D_2^*(2460)^0 \rightarrow D^{*+}\pi^-$, $D^{*+}\pi^-$

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$\left(J^P = 2^+\right)$ and $D_{s1}(2536)^+ \rightarrow D^{*+}K_S^0, D^{*0}K^\pm \left(J^P = 1^+\right)$ and searched for the radially excited state $D^*(2640)^+ \rightarrow D^{*+}\pi^-\pi^-$ ($J^P = 1^- ?$) with a HERA I PHP + DIS sample[9].

A large sample of events has been collected with the ground state charm mesons $D^{*+}, D^0, D^\pm$. The number of $D^{*\pm}$ mesons was obtained by subtracting the wrong charge background. The number of $D^{\pm}$ → $K^+\pi^\pm\pi^\mp$ and $D^0(\bar{D}^0) \rightarrow K^\mp\pi^\pm$ was extracted from fits to a modified Gauss function, $Gauss^{\text{mod}} \sim exp(-0.5x^2 + x + c + xD \pi \pi)$, where $x = (M - \langle M_D \rangle)/\alpha$, plus a background function. For the $D^*$, both $D^0$ decay modes to $K\pi$ and $K\pi\pi\pi$ were used.

### 4.1 Excited charm mesons

To reconstruct the excited charm mesons, a $D^{*\pm}$ or $D^\pm$ candidate was combined with a pion of opposite charge, $\pi_a$. Figure 4 shows the “extended” mass difference distributions $M(D^{*\pm}\pi_a) - M(D^{*\pm}) + M(D^\pm)_{PDG}$ (upper plot) and $M(D^{\pm}\pi_a) - M(D^\pm) + M(D)_{PDG}$ (lower plot). A clear excess is seen in $M(D^{*\pm}\pi_a)$ around the $D_s^0$ mass region. A small excess near the $D_s^0$ mass is seen in $M(D^{\pm}\pi_a^\mp)$. No excess is seen for wrong charge combinations, where $D^*(D)$ and $\pi_a$ have the same charge.

To distinguish between the $D_s^0$ and $D_s^\pm$, the helicity angular distribution, parametrised as $dN/d\cos\alpha \approx 1 + h\cos^2\alpha$, was used. Here $\alpha$ is the angle between the $\pi_a$ and $\pi_S$ momenta in the $D^0$ rest frame. The helicity parameter $h$ is predicted [10] to be $3(-1)$ for pure D-wave $D_s^0 (D_s^\pm)$.

Figure 5 shows the $D^{*}\pi_a$ “extended” mass difference in 4 helicity $|\cos\alpha|$ intervals. The $D_s^0$ contribution increases with $|\cos\alpha|$ and dominates for $|\cos\alpha| > 0.75$. A simultaneous fit was performed to the 4 helicity regions of Fig.5 and to the $M(D\pi)$ distribution of Fig.6. The data is described well with 15 free parameters (signal yields, masses, $D_s^0$ width and helicity). The fitted masses agree with PDG. The fitted $D_s^0$ width is $53.2 \pm 7.2(stat.) ^{+3.3}_{-4.9}(syst.)$ MeV compared to $20.4 \pm 1.7$ MeV of PDG. The fitted $D_s^0$ helicity $(5.9 ^{+3.0}_{-1.7}(stat.) ^{+2.4}_{-1.0}(syst.))$ is consistent with a pure D-wave.
4.2 Excited charm strange mesons

To reconstruct the $D_{s1}^{\pm} \rightarrow D^{\pm} K_S^0$ decays, a $D_{s1}^{\pm}$ candidate was formed by combining a $D^+$ candidate with a reconstructed $K_S^0$ of the same event. Figure 7 (upper plot) shows the “extended” mass difference distribution

$M(D^{*\pm} K_S^0) - M(D^{\pm}) + M(D^*)_{PDG} + M(K_S^0)_{PDG}$. A clear $D_{s1}(2536)^{\pm}$ signal is seen.

The decay mode $D_{s1}^{\pm} \rightarrow D^{*0} K^{\pm}$ is reconstructed from the “extended” mass difference $M(D^{0}K_{s}) - M(D^{0}) + M(D^{0})_{PDG}$. A nice $D_{s1}^{\pm}$ signal is seen (Figure 7 lower plot) at a mass shifted down by $\approx 142$ MeV from the $D_{s1}^{\pm}$ mass. The signal is a feed-down from $D_{s1}^{\pm} \rightarrow D^{*0} K^{\pm}$ with $D^{*0} \rightarrow D^{0} \pi^{0}, D^{0}\gamma$. An unbinned likelihood fit was performed using simultaneously values of $M(D^0K_0), M(D^{*\pm} K_0^0)$ and $\cos \alpha$ for the $D^{*\pm} K_0^0$ combinations. Yields and widths of both signals and the $D_{s1}^{\pm}$ mass and helicity parameter were free parameters of the fit. The fitted $D_{s1}$ helicity parameter is $h(D_{s1}^{\pm}) = -0.74^{+0.23}_{-0.17}(stat.)^{+0.05}_{-0.07}(syst.)$. It is inconsistent with a pure $J^P = 1^+$ D-wave and is barely consistent with a pure $J^P = 1^+$ S-wave, indicating a significant $S-D$ mixing.

The helicity angular distribution form of a $1^+$ state for any D- and S-wave mixing is:

$$dN/d\cos \alpha \sim r + (1-r)(1+3\cos^2 \alpha)/2 + \sqrt{2r(1-r)} \cos \phi (1-3\cos^2 \alpha),$$

where $r = \Gamma_S/\Gamma_D$, $\Gamma_S/\Gamma_D$ is the S/D wave partial width and $\phi$ is relative phase between the 2 amplitudes, $\cos \phi = (\alpha - h)/(\alpha + h) - r$. Figure 8 shows a range, restricted by the measured $h(D_{s1}^{\pm})$ value and its uncertainties, in a plot of $\cos \phi$ versus $r$. The measurement suggests a significant contribution of both D- and S-wave amplitudes to the $D_{s1}(2536)^{\pm} \rightarrow D^{*\pm} K_0^0$ decay. The ZEUS range agrees nicely with the BELLE result and roughly with the CLEO measurement.

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**Figure 7:** $M(D^{*\pm} K_S^0)$ and $M(D^{0} K^{\pm})$ distributions. Solid curves are simultaneous fit; dashed curves are background.

**Figure 6:** $M(D^{\pm} \pi_a)$ distributions in 4 helicity intervals.
5 Branching ratios and fragmentation fractions

Using the ZEUS measured fractions $f(c \rightarrow D^{*+})$ and $f(c \rightarrow D^{0})$, the following decay rate ratios were derived: $B_{D_2^{*0} \rightarrow D^{*+} s^{-}}/B_{D_2^{*0} \rightarrow D^{**+} s^{-}} = 2.8 \pm 0.8^{+0.5}_{-0.6}$ (PDG: 2.3\pm 0.6); $B_{D_1^{*+} \rightarrow D^{0} K^+} = 2.3 \pm 0.6 \pm 0.3$ (PDG: 1.27 \pm 0.21).

Assuming isospin conservation for $D_2^{*0}$ and $D_1^{*+}$ and $B_{D_1^{*+} \rightarrow D^{0} K^+} / B_{D_2^{*0} \rightarrow D^{**+} K^+} = 1$, yields a strangeness suppression of excited $D$ mesons $f(c \rightarrow D_1^{*+}) / f(c \rightarrow D_2^{*0}) = 0.31 \pm 0.06(stat.) ^{+0.05}_{-0.04}(syst.)$.

In Table 2 the ZEUS fragmentation fractions of the excited charm mesons are compared with $e^+ e^-$ values. The results are consistent within errors.

DELPHI saw a narrow peak in $D^{*\pm} \pi^+ \pi^-$ at 2637 MeV [12] and attributed it to a radially excited $D^{*\pm}$. No signal was seen in ZEUS and a 95% C.L. upper limit of $f(c \rightarrow D^{*\pm}) \cdot B_{D^{*\pm} \rightarrow D^{0} \pi^+ \pi^-} < 0.4\%$ was set, compared to the weaker limit of OPAL (0.9\%) [13].

|          | $f(c \rightarrow D_1^{*+})[\%]$ | $f(c \rightarrow D_2^{*0})[\%]$ | $f(c \rightarrow D_1^{*+})[\%]$ |
|----------|---------------------------------|---------------------------------|---------------------------------|
| ZEUS     | $3.5 \pm 0.4^{+0.4}_{-0.6}$     | $3.8 \pm 0.7^{+0.5}_{-0.6}$     | $1.11 \pm 0.16^{+0.05}_{-0.10}$ |
| OPAL     | $2.1 \pm 0.8$                   | $5.2 \pm 2.6$                   | $1.6 \pm 0.4 \pm 0.3$          |
| ALEPH    |                                 |                                 | $0.94 \pm 0.22 \pm 0.07$       |

Table 2: The fractions of $c$ quarks hadronising into $D_1^{*+}$, $D_2^{*0}$ and $D_1^{*+}$ mesons.

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