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# Inclusive $K^0_S K^0_S$ Resonance Production in $ep$ Collisions at HERA

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Inclusive $K^0_S K^0_S$ production in $ep$ collisions at the DESY $ep$ collider HERA was studied with the ZEUS detector using an integrated luminosity of 0.5 $\text{fb}^{-1}$. Enhancements in the mass spectrum were observed and are attributed to the production of $f_2(1270)/a^0_2(1320)$, $f'_2(1525)$ and $f_0(1710)$. Masses and widths were obtained using a fit which takes into account theoretical predictions based on SU(3) symmetry arguments, and are consistent with the Particle Data Group values. The $f_0(1710)$ state, which has a mass consistent with a glueball candidate, was observed with a statistical significance of 5 standard deviations. However, if this state is the same as that seen in $\gamma\gamma \to K^0_S K^0_S$, it is unlikely to be a pure glueball state.

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*Introduction.*—The existence of glueballs is predicted by QCD. The lightest glueball is expected to have quantum numbers $J^{\mathrm{PC}} = 0^{++}$ and a mass in the range 1550–1750 MeV [1]. Thus, it can mix with $q\bar{q}$ states from the scalar meson nonet, which have $I = 0$ and similar masses. Four states with $J^{\mathrm{PC}} = 0^{++}$ and $I = 0$ are established [1]: $f_0(980)$, $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$, but only two states can fit into the nonet. In the literature, the state $f_0(1710)$ is frequently considered to be a state with a possible glueball or tetraquark composition [2]. However, its partonic content has yet to be established.

The ZEUS Collaboration previously observed [3] indications of two states, $f'_2(1525)$ and $f_0(1710)$, decaying to $K^0_S K^0_S$ final states in inclusive deep inelastic scattering (DIS) events. The statistical significance of the observation did not exceed three standard deviations. The state in the 1700 MeV mass region had a mass consistent with that of the $f_0(1710)$; however, its width was significantly narrower than that quoted by the Particle Data Group (PDG) [1].

The results presented here correspond to the full HERA luminosity of 0.5 $\mathrm{fb}^{-1}$ and supersede the earlier ZEUS results. The measurement of the $K^0_S K^0_S$ final states is presented in a kinematic region of $ep$ collisions dominated by photoproduction with exchanged photon virtuality, $Q^2$, below 1 $\mathrm{GeV}^2$. The data allow the reconstruction of the $K^0_S K^0_S$ final states with much larger statistics than previously used.

*Experimental setup.*—The data were collected between 1996 and 2007 at the electron-proton collider HERA using the ZEUS detector. During this period HERA operated with electrons or positrons (Here and in the following, the term "electron" denotes generically both the electron ($e^-$) and the positron ($e^+$).) of energy $E_e = 27.5$ GeV and protons initially with an energy of 820 GeV and, after 1997, with 920 GeV.

A detailed description of the ZEUS detector can be found elsewhere [4]. Charged particles were tracked in the central tracking detector [5], which operated in a magnetic field of 1.43 T provided by a thin superconducting solenoid. Before the 2004–2007 running period, the ZEUS tracking system was upgraded with a silicon Micro Vertex Detector (MVD) [6]. The high-resolution uranium-scintillator calorimeter (CAL) [7] consisted of three parts: the forward, the barrel, and the rear calorimeters.

*Event sample.*—A three-level trigger system [4,8] was used to select events online. No explicit trigger requirement was applied for selecting $K^0_S K^0_S$ events. The photoproduction sample is dominated by events triggered by a low jet transverse energy, $E_T$, requirement ($E_T > 6$ GeV). Deep inelastic scattering events were triggered by requiring an electron in the CAL.

Events were selected offline by requiring $|Z_{\mathrm{vtx}}| < 50$ cm, where $Z_{\mathrm{vtx}}$ is the $Z$ coordinate of the primary vertex position determined from the tracks. The average energy of the total hadronic system, $W$, of the selected events was $\approx 200$ GeV. The data sample was dominated by photoproduction events with $Q^2 < 1$ $\mathrm{GeV}^2$.

*Reconstruction of $K^0_S$ candidates.*—The $K^0_S$ mesons were identified via their charged-decay mode, $K^0_S \to \pi^+\pi^-$. Both tracks from the same secondary decay vertex were assigned the mass of the charged pion and the invariant mass, $M(\pi^+\pi^-)$, of each track pair was calculated. The $K^0_S$ candidates were selected by requiring: (i) $M(e^+e^-) \geq 50$ MeV, where the electron mass was assigned to each track, to eliminate tracks from photon conversions; (ii) $M(p\pi) \geq 1121$ MeV, where the proton mass was assigned to the track with higher momentum, to eliminate $\Lambda$ and $\bar{\Lambda}$ contamination to the $K^0_S$ signal; (iii) $p_T(K^0_S) \geq 0.25$ GeV and $|\eta(K^0_S)| \leq 1.6$, where $p_T(K^0_S)$ is the transverse momentum and $\eta(K^0_S)$ is the pseudorapidity; (iv) $\theta_{2\mathrm{D}} < 0.12$ rad ($\theta_{3\mathrm{D}} < 0.24$ rad), where $\theta_{2\mathrm{D}}$ ($\theta_{3\mathrm{D}}$) is the two (three) dimensional collinearity angle between the $K^0_S$-candidate momentum vector and the vector defined by the interaction point and the $K^0_S$ decay vertex. For $\theta_{2\mathrm{D}}$, the $XY$ plane was used.

The cuts on the collinearity angles significantly reduced the non-$K^0_S$ background in the data during the 2004–2007 period. These cuts were necessary due to the extra material introduced by the MVD. After all these cuts, the decay length distribution of the resulting $K^0_S$ candidates peaked at $\approx 2$ cm.

Events with at least two $K^0_S$ candidates were accepted for further analysis. More than two $K^0_S$ were allowed in one event, unlike for the previously published result [3], and all distinct combinations of $K^0_S K^0_S$ were used. In the mass range of $481 \leq M(\pi^+\pi^-) \leq 515$ MeV the number of $K^0_S$ candidates is 1258399.

Figure 1 shows the invariant-mass distribution of $K^0_S$ candidates. A fit over the whole mass range including a first-order polynomial was used to estimate the background contribution at $\sim 8\%$. The central region was fitted with two bifurcated Gaussian functions to determine the mass and width of the $K^0_S$ meson. For the HERA II data, corrections were applied to take into account the extra dead material introduced into the detector. After the corrections, the mass and width of the $K^0_S$ were compatible with the PDG value and detector resolution, respectively.

*Results.*—The $K^0_S K^0_S$ invariant-mass distribution was reconstructed by combining two $K^0_S$ candidates selected in the mass window $481 \leq M(\pi^+\pi^-) \leq 515$ MeV. Tracks used for the $K^0_S K^0_S$ pair reconstruction were required to be assigned uniquely to each $K^0_S$ in the $K^0_S K^0_S$ pair.

Figure 2(a) shows the measured $K^0_S K^0_S$ invariant-mass spectrum. Three peaks are seen at around 1300, 1500, and 1700 MeV. No state heavier than the $f_0(1710)$ was observed. The invariant-mass distribution, $m$, was fitted as a sum of resonance production and a smoothly varying background $U(m)$. Each resonant amplitude, $R$, was given a relativistic Breit-Wigner form [9]:

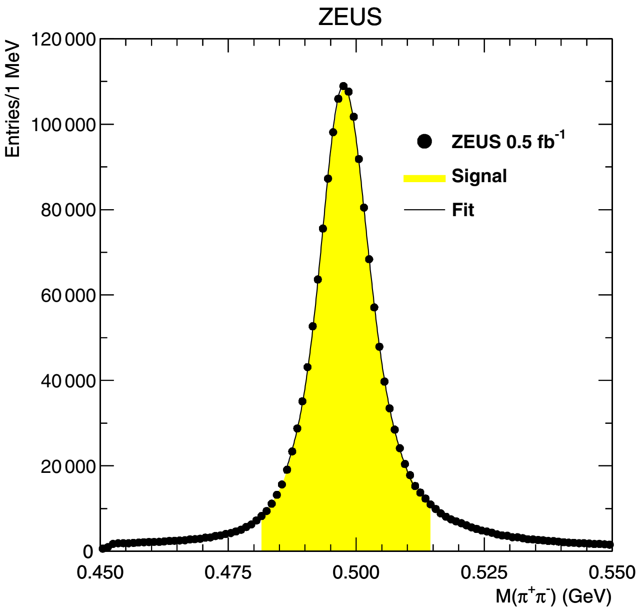

FIG. 1 (color online). The measured $\pi^+\pi^-$ invariant-mass distribution for events with at least two $K_S^0$ candidates (dots). The shaded area represents the signal window used for $K_S^0K_S^0$ pair reconstruction. The fit performed (see text) is displayed as a solid line.

$$BW(R) = \frac{M_R\sqrt{\Gamma_R}}{M_R^2 - m^2 - iM_R\Gamma_R}, \tag{1}$$

where $M_R$ and $\Gamma_R$ are the resonance mass and width, respectively. The background function used was

$$U(m) = m^A \exp(-Bm), \tag{2}$$

where $A$ and $B$ are free parameters. The $K_S^0K_S^0$ mass resolution is about 12 MeV for the mass region below 1800 MeV and its impact on the extracted widths is small compared to the expected widths of the states [3]. Therefore, resolution effects were ignored in the fit.

Two types of fit, as performed for the reaction $\gamma\gamma \to K_S^0K_S^0$ by the L3 [10] and TASSO [9] Collaborations, respectively, were tried, using Eqs. (1) and (2). Fit 1 is an incoherent sum of three Breit-Wigner cross sections representing the $f_2(1270)/a_2^0(1320)$, $f_2'(1525)$ and $f_0(1710)$ plus background. Fit 2 is motivated by SU(3) predictions [11]. 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 three amplitudes plus the incoherent addition of $f_0(1710)$ and a nonresonant background. The predicted coefficients of the $f_2(1270)$, $a_2^0(1320)$, and $f_2'(1525)$ Breit-Wigner amplitudes for an electromagnetic production process are, respectively, +5, −3, and +2 [11,12]. This results in the fit function:

$$\begin{aligned} F(m) = a|&5BW(f_2(1270)) - 3BW(a_2^0(1320)) \\ &+ 2BW(f_2'(1525))|^2 + b|BW(f_0(1710))|^2 \\ &+ cU(m), \end{aligned} \tag{3}$$

where $a$, $b$, and $c$ are free parameters.

All the resonance masses and widths were allowed to vary in the fits. The results of the fits are shown in Table I. The quality of both fits, characterized by the $\chi^2$ per number of degrees of freedom (see Table I), is good. However, fit 2 describes the spectrum around the $f_2(1270)/a_2^0(1320)$ region better and, unlike fit 1, reproduces the dip between $f_2(1270)/a_2^0(1320)$ and $f_2'(1525)$. For this reason and, based on the theoretical motivation, fit 2 is preferred and shown in Fig. 2. The background-subtracted mass spectrum is shown in Fig. 2(b) together with the fit.

The $a_2^0(1320)$ mass in fit 2 is below the PDG value [1]. A similar shift, attributed to the destructive interference between $f_2(1270)$ and $a_2^0(1320)$, was also seen in a study of resonance physics with $\gamma\gamma$ events [11]. Fit 1 without interference yields a narrow width for the combined $f_2(1270)/a_2^0(1320)$ peak, as also seen by the L3 Collaboration [10]. Fit 2 with interference yields widths close to the PDG values for all observed resonances. The fitted masses for $f_2'(1525)$ and $f_0(1710)$ are somewhat below the PDG values with uncertainties comparable with those of the PDG (Table I). The quality of a fit without

TABLE I. The measured masses and widths for the $f_2(1270)$, $a_2^0(1320)$, $f_2'(1525)$ and $f_0(1710)$ states using $K_S^0K_S^0$ decays as determined by one fit neglecting interference and another one with interference as predicted by SU(3) symmetry arguments included. Both statistical and systematic uncertainties are quoted. The systematic uncertainty for the $f_2(1270)/a_2^0(1320)$ peak is expected to be significant and it is not listed. Also quoted are the PDG values for comparison.

| Fit | No interference | | Interference | | PDG 2007 Values | |
|---|---|---|---|---|---|---|
| $\chi^2$/ndf | 96/95 | | 86/97 | | | |
| in MeV | Mass | Width | Mass | Width | Mass | Width |
| $f_2(1270)$ | $1304 \pm 6$ | $61 \pm 11$ | $1268 \pm 10$ | $176 \pm 17$ | $1275.4 \pm 1.1$ | $185.2^{+3.1}_{-2.5}$ |
| $a_2^0(1320)$ | | | $1257 \pm 9$ | $114 \pm 14$ | $1318.3 \pm 0.6$ | $107 \pm 5$ |
| $f_2'(1525)$ | $1523 \pm 3^{+2}_{-8}$ | $71 \pm 5^{+17}_{-2}$ | $1512 \pm 3^{+1.4}_{-0.5}$ | $83 \pm 9^{+5}_{-4}$ | $1525 \pm 5$ | $73^{+6}_{-5}$ |
| $f_0(1710)$ | $1692 \pm 6^{+9}_{-3}$ | $125 \pm 12^{+19}_{-32}$ | $1701 \pm 5^{+9}_{-2}$ | $100 \pm 24^{+7}_{-22}$ | $1724 \pm 7$ | $137 \pm 8$ |

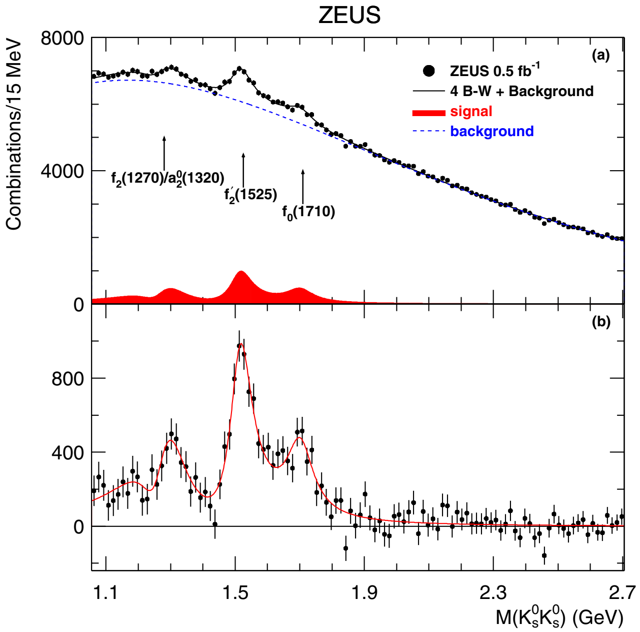

FIG. 2 (color online). (a) The measured $K_S^0K_S^0$ invariant-mass spectrum (dots). The solid line is the result of the fit described as fit 2 in the text [Eq. (3)] and the dashed line represents the background function. (b) Background-subtracted $K_S^0K_S^0$ invariant-mass spectrum (dots); the result of the fit is shown as a solid line.

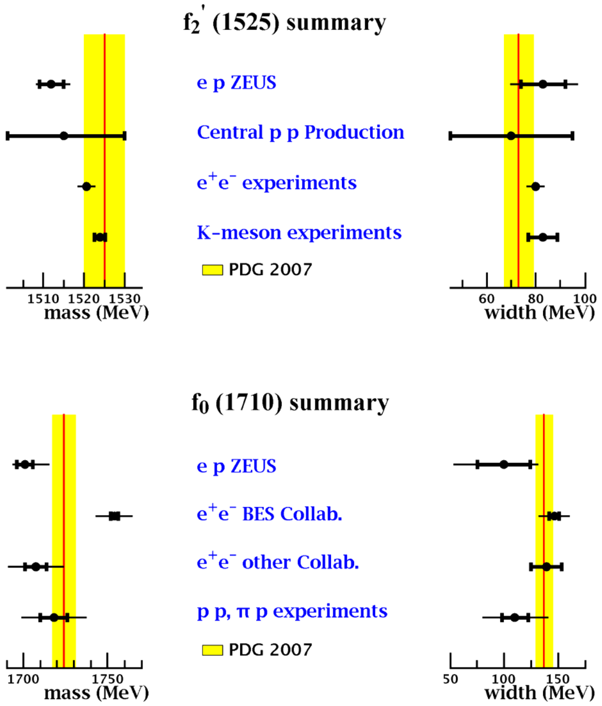

FIG. 3 (color online). Comparison of the present mass and width measurements of the $f_2'(1525)$ and $f_0(1710)$ states with other selected measurements [1]. The bands show the PDG values and error estimates.

the $f_0(1710)$ resonance (not shown) yields $\chi^2/\mathrm{ndf} = 162/97$ and is strongly disfavored.

The systematic uncertainties of the masses and widths of the resonances, determined from the fit shown in Fig. 2, were evaluated by changing the selection cuts and the fitting procedure. Variations of minimum track $p_T$, track pseudorapidity range, track momenta by ±0.1%, accepted $\pi^+\pi^-$ mass range around the $K_S^0$ peak and collinearity cuts were done. In addition a maximum likelihood fit was used instead of the $\chi^2$ fit and event selection cuts were varied. A check for the possible influence of the $J^P = 0^+$ state $f_0(1500)$ was carried out by including in the fit a Breit-Wigner amplitude of this state interfering with the amplitude of the $f_0(1710)$. The resulting changes of the fitted values of the mass and the width of the $f_0(1710)$ are included in the systematic uncertainties [13]. The largest systematic uncertainties were: fitting with fixed PDG mass and width on $f_2'(1525)$ affects the $f_0(1710)$ width by $-19$ MeV and the largest effect of varying the track momenta on the $f_0(1710)$ width is $+7$ MeV. The combined systematic uncertainties are included in Table I.

The number of events in the $f_0(1710)$ resonance given by the fit is $4058 \pm 820$, which has a 5 standard deviation statistical significance. This is one of the best $f_0(1710)$ signals reported. This state is considered to be a glueball candidate [2]. However, if it is the same as seen in $\gamma\gamma \to K_S^0K_S^0$ [9,10], it is unlikely to be a pure glueball state, since photons can couple in partonic level only to charged objects. Figure 3 compares the results of this analysis with other measurements from collider and fixed-target experiments. The $f_0(1710)$ mass as deduced from the quarkonium decays by the BES Collaboration is significantly higher than the values given by all other experiments, including older $J/\psi$-decay analyses [1].

*Conclusions.*—In conclusion, $K_S^0K_S^0$ final states were studied in $ep$ collisions at HERA with the ZEUS detector. Three enhancements which correspond to $f_2(1270)/a_2^0(1320)$, $f_2'(1525)$ and $f_0(1710)$ were observed. No state heavier than the $f_0(1710)$ was observed. The states were fitted taking into account the interference pattern predicted by SU(3) symmetry arguments. The measured masses of the $f_2'(1525)$ and $f_0(1710)$ states are somewhat below the world average; however, the widths are consistent with the PDG values. The $f_0(1710)$ state, which has a mass consistent with a $J^{PC} = 0^{++}$ glueball candidate, is observed with a 5 standard-deviation statistical significance. However, if this state is the same as that seen in $\gamma\gamma \to K_S^0K_S^0$, it is unlikely to be a pure glueball state.

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