Available online at www.sciencedirect.com
SCIENCE DIRECT
Physics Letters B 578 (2004) 33–44
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Observation of $K_s^0 K_s^0$ resonances in deep inelastic scattering at HERA

ZEUS Collaboration

S. Chekanov, M. Derrick, D. Krakauer, J.H. Loizides [1], S. Magill, B. Musgrave, J. Repond, R. Yoshida

Argonne National Laboratory, Argonne, IL 60439-4815, USA [46]

M.C.K. Mattingly

Andrews University, Berrien Springs, MI 49104-0380, USA

P. Antonioli, G. Bari, M. Basile, L. Bellagamba, D. Boscherini, A. Bruni, G. Bruni, G. Cara Romeo, L. Cifarelli, F. Cindolo, A. Contin, M. Corradi, S. De Pasquale, P. Giusti, G. Iacobucci, A. Margotti, A. Montanari, R. Nania, F. Palmonari, A. Pesci, G. Sartorelli, A. Zichichi

University and INFN Bologna, Bologna, Italy [37]

G. Aghuzumtsyan, D. Bartsch, I. Brock, S. Goers, H. Hartmann, E. Hilger, P. Irrgang, H.-P. Jakob, A. Kappes [2], U.F. Katz [2], O. Kind, U. Meyer, E. Paul [3], J. Rautenberg, R. Renner, A. Stifutkin, J. Tandler, K.C. Voss, M. Wang, A. Weber [4]

Physikalisches Institut der Universität Bonn, Bonn, Germany [34]

D.S. Bailey [5], N.H. Brook [5], J.E. Cole, B. Foster, G.P. Heath, H.F. Heath, S. Robins, E. Rodrigues [6], J. Scott, R.J. Tapper, M. Wing

H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom [45]

M. Capua, A. Mastroberardino, M. Schioppa, G. Susinno

Calabria University, Physics Department and INFN, Cosenza, Italy [37]

J.Y. Kim, Y.K. Kim, J.H. Lee, I.T. Lim, M.Y. Pac [7]

Chonnam National University, Kwangju, South Korea [39]

0370-2693/\$ – see front matter
doi:10.1016/j.physletb.2003.10.049

A. Caldwell [8], M. Helbich, X. Liu, B. Mellado, Y. Ning, S. Paganis, Z. Ren, W.B. Schmidke, F. Sciulli

Nevis Laboratories, Columbia University, Irvington on Hudson, NY 10027, USA [47]

J. Chwastowski, A. Eskreys, J. Figiel, K. Olkiewicz, P. Stopa, L. Zawiejski

Institute of Nuclear Physics, Cracow, Poland [41]

L. Adamczyk, T. Bołd, I. Grabowska-Bołd, D. Kisielewska, A.M. Kowal, M. Kowal, T. Kowalski, M. Przybycień, L. Suszycki, D. Szuba, J. Szuba [9]

Faculty of Physics and Nuclear Techniques, AGH-University of Science and Technology, Cracow, Poland [48]

A. Kotański [10], W. Słomiński [11]

Department of Physics, Jagellonian University, Cracow, Poland

V. Adler, L.A.T. Bauerdick [12], U. Behrens, I. Bloch, K. Borras, V. Chiochia, D. Dannheim, G. Drews, J. Fourletova, U. Fricke, A. Geiser, P. Göttlicher [13], O. Gutsche, T. Haas, W. Hain, G.F. Hartner, S. Hillert, B. Kahle, U. Kötz, H. Kowalski [14], G. Kramberger, H. Labes, D. Lelas, B. Löhr, R. Mankel, I.-A. Melzer-Pellmann, M. Moritz [15], C.N. Nguyen, D. Notz, M.C. Petrucci [16], A. Polini, A. Raval, L. Rurua, U. Schneekloth, F. Selonke [3], U. Stoesslein, H. Wessoleck, G. Wolf, C. Youngman, W. Zeuner

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

S. Schlenstedt

DESY Zeuthen, Zeuthen, Germany

G. Barbagli, E. Gallo, C. Genta, P.G. Pelfer

University and INFN, Florence, Italy [37]

A. Bamberger, A. Benen, N. Coppola

Fakultät für Physik der Universität Freiburg i.Br., Freiburg i.Br., Germany [34]

M. Bell, P.J. Bussey, A.T. Doyle, J. Hamilton, S. Hanlon, S.W. Lee, A. Lupi, D.H. Saxon, I.O. Skillicorn

Department of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom [45]

I. Gialas

Department of Engineering in Management and Finance, University of Aegean, Greece

B. Bodmann, T. Carli, U. Holm, K. Klimek, N. Krumnack, E. Lohrmann, M. Milite, H. Salehi, S. Stonjek [17], K. Wick, A. Ziegler, Ar. Ziegler

Hamburg University, Institute of Experimental Physics, Hamburg, Germany [34]

C. Collins-Tooth, C. Foudas, R. Gonçalo [6], K.R. Long, A.D. Tapper

Imperial College London, High Energy Nuclear Physics Group, London, United Kingdom [45]

P. Cloth, D. Filges

Forschungszentrum Jülich, Institut für Kernphysik, Jülich, Germany

K. Nagano, K. Tokushuku [18], S. Yamada, Y. Yamazaki, M. Kataoka [19]

Institute of Particle and Nuclear Studies, KEK, Tsukuba, Japan [38]

A.N. Barakbaev, E.G. Boos, N.S. Pokrovskiy, B.O. Zhautykov

Institute of Physics and Technology of Ministry of Education and Science of Kazakhstan, Almaty, Kazakhstan

H. Lim, D. Son

Kyungpook National University, Taegu, South Korea [39]

K. Piotrzkowski

Institut de Physique Nucléaire, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

F. Barreiro, C. Glasman [20], O. González, L. Labarga, J. del Peso, E. Tassi, J. Terrón, M. Vázquez

Departamento de Física Teórica, Universidad Autónoma de Madrid, Madrid, Spain [44]

M. Barbi, F. Corriveau, S. Gliga, J. Lainesse, S. Padhi, D.G. Stairs, R. Walsh

Department of Physics, McGill University, Montréal, Québec H3A 2T8, Canada [33]

T. Tsurugai

Meiji Gakuin University, Faculty of General Education, Yokohama, Japan [38]

A. Antonov, P. Danilov, B.A. Dolgoshein, D. Gladkov, V. Sosnovtsev, S. Suchkov

Moscow Engineering Physics Institute, Moscow, Russia [42]

R.K. Dementiev, P.F. Ermolov, Yu.A. Golubkov, I.I. Katkov, L.A. Khein, I.A. Korzhavina, V.A. Kuzmin, B.B. Levchenko [21], O.Yu. Lukina, A.S. Proskuryakov, L.M. Shcheglova, N.N. Vlasov, S.A. Zotkin

Moscow State University, Institute of Nuclear Physics, Moscow, Russia [43]

N. Coppola, S. Grijpink, E. Koffeman, P. Kooijman, E. Maddox, A. Pellegrino, S. Schagen, H. Tiecke, J.J. Velthuis, L. Wiggers, E. de Wolf

NIKHEF and University of Amsterdam, Amsterdam, Netherlands [40]

N. Brümmer, B. Bylsma, L.S. Durkin, T.Y. Ling

Physics Department, Ohio State University, Columbus, OH 43210, USA [46]

A.M. Cooper-Sarkar, A. Cottrell, R.C.E. Devenish, J. Ferrando, G. Grzelak, C. Gwenlan, S. Patel, M.R. Sutton, R. Walczak

Department of Physics, University of Oxford, Oxford, United Kingdom [45]

A. Bertolin, R. Brugnera, R. Carlin, F. Dal Corso, S. Dusini, A. Garfagnini, S. Limentani, A. Longhin, A. Parenti, M. Posocco, L. Stanco, M. Turcato

Dipartimento di Fisica dell' Università and INFN, Padova, Italy [37]

E.A. Heaphy, F. Metlica, B.Y. Oh, J.J. Whitmore [22]

Department of Physics, Pennsylvania State University, University Park, PA 16802, USA [47]

Y. Iga

Polytechnic University, Sagamihara, Japan [38]

G. D'Agostini, G. Marini, A. Nigro

Dipartimento di Fisica, Università 'La Sapienza' and INFN, Rome, Italy [37]

C. Cormack [23], J.C. Hart, N.A. McCubbin

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, United Kingdom [45]

C. Heusch

University of California, Santa Cruz, CA 95064, USA [46]

I.H. Park

Department of Physics, Ewha Womans University, Seoul, South Korea

N. Pavel

Fachbereich Physik der Universität-Gesamthochschule Siegen, Germany

H. Abramowicz, A. Gabareen, S. Kananov, A. Kreisel, A. Levy

Raymond and Beverly Sackler Faculty of Exact Sciences, School of Physics, Tel-Aviv University, Tel-Aviv, Israel [36]

M. Kuze

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan [38]

T. Abe, T. Fusayasu, S. Kagawa, T. Kohno, T. Tawara, T. Yamashita

Department of Physics, University of Tokyo, Tokyo, Japan [38]

R. Hamatsu, T. Hirose [3], M. Inuzuka, H. Kaji, S. Kitamura [24], K. Matsuzawa, T. Nishimura

Department of Physics, Tokyo Metropolitan University, Tokyo, Japan [38]

M. Arneodo [25], M.I. Ferrero, V. Monaco, M. Ruspa, R. Sacchi, A. Solano

Università di Torino, Dipartimento di Fisica Sperimentale and INFN, Torino, Italy [37]

T. Koop, G.M. Levman, J.F. Martin, A. Mirea

Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada [33]

J.M. Butterworth, R. Hall-Wilton, T.W. Jones, M.S. Lightwood, B.J. West

Physics and Astronomy Department, University College London, London, United Kingdom [45]

J. Ciborowski [26], R. Ciesielski [27], P. Łużniak [28], R.J. Nowak, J.M. Pawlak, J. Sztuk [29], T. Tymieniecka [30], A. Ukleja [30], J. Ukleja [31], A.F. Żarnecki

Warsaw University, Institute of Experimental Physics, Warsaw, Poland [49]

M. Adamus, P. Plucinski

Institute for Nuclear Studies, Warsaw, Poland [49]

Y. Eisenberg, L.K. Gladilin [32], D. Hochman, U. Karshon, M. Riveline

Department of Particle Physics, Weizmann Institute, Rehovot, Israel [35]

D. Kçira, S. Lammers, L. Li, D.D. Reeder, M. Rosin, A.A. Savin, W.H. Smith

Department of Physics, University of Wisconsin, Madison, WI 53706, USA [46]

A. Deshpande, S. Dhawan, P.B. Straub

Department of Physics, Yale University, New Haven, CT 06520-8121, USA [46]

S. Bhadra, C.D. Catterall, S. Fourletov, G. Hartner, S. Menary, M. Soares, J. Standage

Department of Physics, York University, Ontario M3J 1P3, Canada [33]

Received 1 August 2003; accepted 15 October 2003
Editor: W.-D. Schlatter

Abstract

Inclusive $K_s^0 K_s^0$ production in deep inelastic *ep* scattering at HERA has been studied with the ZEUS detector using an integrated luminosity of 120 pb^{-1}. Two states are observed at masses of 1537^{+9}_{-8} MeV and 1726 ± 7 MeV, as well as an enhancement around 1300 MeV. The state at 1537 MeV is consistent with the well established $f_2'(1525)$. The state at 1726 MeV may be the glueball candidate $f_0(1710)$. However, it's width of 38^{+20}_{-14} MeV is narrower than 125 ± 10 MeV observed by previous experiments for the $f_0(1710)$.

E-mail address: rik.yoshida@desy.de (R. Yoshida).

[1] Also affiliated with University College London.

[2] On leave of absence at University of Erlangen-Nürnberg, Germany.

[3] Retired.

[4] Self-employed.

[5] PPARC Advanced fellow.

[6] Supported by the Portuguese Foundation for Science and Technology (FCT).

[7] Now at Dongshin University, Naju, South Korea.

[8] Now at Max-Planck-Institut für Physik, München, Germany.

[9] Partly supported by the Israel Science Foundation and the Israel Ministry of Science.

[10] Supported by the Polish State Committee for Scientific Research, grant No. 2 P03B 09322.

[11] Member of Department of Computer Science.

[12] Now at Fermilab, Batavia, IL, USA.

[13] Now at DESY group FEB.

[14] On leave of absence at Columbia University, Nevis Labs., NY, USA.

[15] Now at CERN.

[16] Now at INFN Perugia, Perugia, Italy.

[17] Now at University of Oxford, Oxford, UK.

[18] Also at University of Tokyo.

[19] Also at Nara Women's University, Nara, Japan.

[20] Ramón y Cajal Fellow.

[21] Partly supported by the Russian Foundation for Basic Research, grant 02-02-81023.

[22] On leave of absence at The National Science Foundation, Arlington, VA, USA.

[23] Now at University of London, Queen Mary College, London, UK.

[24] Present address: Tokyo Metropolitan University of Health Sciences, Tokyo 116-8551, Japan.

[25] Also at Università del Piemonte Orientale, Novara, Italy.

[26] Also at Łódź University, Poland.

[27] Supported by the Polish State Committee for Scientific Research, grant No. 2 P03B 07222.

[28] Łódź University, Poland.

[29] Łódź University, Poland, supported by the KBN grant 2P03B12925.

[30] Supported by German Federal Ministry for Education and Research (BMBF), POL 01/043.

[31] Supported by the KBN grant 2P03B12725.

[32] On leave from MSU, partly supported by University of Wisconsin via the US–Israel BSF.

[33] Supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

[34] Supported by the German Federal Ministry for Education and Research (BMBF), under contract numbers HZ1GUA 2, HZ1GUB 0, HZ1PDA 5, HZ1VFA 5.

[35] Supported by the MINERVA Gesellschaft für Forschung GmbH, the Israel Science Foundation, the US–Israel Binational Science Foundation and the Benozyio Center for High Energy Physics.

[36] Supported by the German–Israeli Foundation and the Israel Science Foundation.

[37] Supported by the Italian National Institute for Nuclear Physics (INFN).

[38] Supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and its grants for Scientific Research.

[39] Supported by the Korean Ministry of Education and Korea Science and Engineering Foundation.

[40] Supported by the Netherlands Foundation for Research on Matter (FOM).

[41] Supported by the Polish State Committee for Scientific Research, grant No. 620/E-77/SPB/DESY/P-03/DZ 117/2003-2005.

[42] Partially supported by the German Federal Ministry for Education and Research (BMBF).

[43] Supported by the Fund for Fundamental Research of Russian Ministry for Science and Education and by the German Federal Ministry for Education and Research (BMBF).

[44] Supported by the Spanish Ministry of Education and Science through funds provided by CICYT.

[45] Supported by the Particle Physics and Astronomy Research Council, UK.

1. Introduction

The $K_s^0 K_s^0$ system is expected to couple to scalar and tensor glueballs. This has motivated intense experimental and theoretical study during the past few years [1,2]. Lattice QCD calculations [3] predict the existence of a scalar glueball with a mass of 1730 ± 100 MeV and a tensor glueball at 2400 ± 120 MeV. The scalar glueball can mix with $q\bar{q}$ states with $I = 0$ from the scalar meson nonet, leading to three $J^{PC} = 0^{++}$ states, whereas only two can fit into the nonet. Experimentally, four states with $J^{PC} = 0^{++}$ and $I = 0$ have been established [4]: $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$.

The state most frequently considered to be a glueball candidate is $f_0(1710)$ [4], but its gluon content has not yet been established. This state was first observed in radiative J/ψ decays [5] and its angular momentum $J = 0$ was established by the WA102 experiment using a partial-wave analysis in the K^+K^- and $K_s^0 K_s^0$ final states [6]. A recent publication from L3 [7] reports the observation of two states in $\gamma\gamma$ collisions above 1500 MeV, the well established $f_2'(1525)$ [4] and a broad resonance at 1760 MeV. It is not clear if this state is the $f_0(1710)$. Observation of $f_0(1710)$ in $\gamma\gamma$ collisions would indicate a large quark content.

The *ep* collisions at HERA provide an opportunity to study resonance production in a new environment. The production of K_s^0 has been studied previously at HERA [8,9]. In this Letter, the first observation of resonances in the $K_s^0 K_s^0$ final state in inclusive *ep* deep inelastic scattering (DIS) is reported.

2. Experimental set-up

The data were collected by the ZEUS detector at HERA during the 1996–2000 running periods. In 1996–1997, HERA collided 27.5 GeV positrons with 820 GeV protons. In 1998–2000, the proton energy was 920 GeV and both positrons and electrons were collided with protons. The measurements for e^+p (e^-p) interactions[50] are based on an integrated luminosity of 104 pb^{-1} (17 pb^{-1}).

A detailed description of the ZEUS detector can be found elsewhere [10]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles are tracked in the central tracking detector (CTD) [11], which operates in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD consists of 72 cylindrical drift chamber layers, organized in nine superlayers covering the polar-angle[51] region $15° < \theta < 164°$. The relative transverse-momentum resolution for full-length tracks is $\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV. The tracking system was used to establish the primary and secondary vertices.

The high-resolution uranium-scintillator calorimeter (CAL) [12] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is 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 is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons, with E in GeV.

The energy of the scattered electron was corrected for energy loss in the material between the interaction point and the calorimeter using a small-angle rear tracking detector (SRTD) [13,14] and a presampler (PRES) [14,15].

46 Supported by the US Department of Energy.

47 Supported by the US National Science Foundation.

48 Supported by the Polish State Committee for Scientific Research, grant No. 112/E-356/SPUB/DESY/P-03/DZ 116/2003-2005, 2 P03B 13922.

49 Supported by the Polish State Committee for Scientific Research, grant No. 115/E-343/SPUB-M/DESY/P-03/DZ 121/2001-2002, 2 P03B 07022.

50 Hereafter, both e^+ and e^- are referred to as electrons, unless explicitly stated otherwise.

51 The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the “forward direction”, and the X axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point.

3. Kinematic reconstruction and event selection

The inclusive neutral current DIS process $e(k) + p(P) \to e(k') + X$ can be described in terms of the following variables: the negative of the invariant mass squared of the exchanged virtual photon, $Q^2 = -q^2 = -(k-k')^2$; the fraction of the lepton energy transferred to the proton in the proton rest frame, $y = (q \cdot P)/(k \cdot P)$; and the Bjorken scaling variable, $x = Q^2/(2P \cdot q)$.

A three-level trigger system was used to select events online [10]. The inclusive DIS selection was defined by requiring an electron found in the CAL. In certain run periods, corresponding to 83% of the total luminosity, the inclusive selection was not available for low Q^2 ($Q^2 < 20$ GeV^2) events. For these periods, an additional selection with a requirement of at least one forward jet identified with the k_t algorithm [16] and having transverse energy $E_T > 3$ GeV ($E_T > 4$ GeV in the 2000 running period), pseudorapidity $0 < \eta_{\rm jet} < 3$ ($1.5 < \eta_{\rm jet} < 3.5$ in the 1996–1997 running period) was used.

The DIS offline event selection was based on the following requirements:

- a primary vertex position, determined from the tracks fitted to the vertex, in the range $|Z_{\rm vertex}| < 50$ cm, to reduce the background events from non-*ep* interactions;
- $E_e \geqslant 8.5$ GeV, where E_e is the energy of the scattered electron reconstructed in the calorimeter;
- $42 < \delta < 60$ GeV, where $\delta = \sum E_i(1-\cos\theta_i)$, E_i is the energy of the ith calorimeter cell and θ_i is its polar angle as viewed from the primary vertex. The sum runs over all cells. This cut further reduces the background from photoproduction and events with large QED initial-state radiation;
- $y_{\rm e} \leqslant 0.95$, to remove events with misidentified scattered DIS electrons; $y_{\rm e}$ is the value of y reconstructed using the scattered electron measurements;
- $y_{\rm JB} \geqslant 0.04$, to remove events with low hadronic activities; $y_{\rm JB}$ is the value of y reconstructed using the Jaquet–Blondel method [17];
- the position of the scattered lepton candidate in the RCAL was required to be outside a box of ± 14 cm in X and Y, which corresponds approximately to $\theta_{\rm ele} \approx 176^\circ$, where $\theta_{\rm ele}$ is the polar angle of the scattered electron;
- a maximum of 40 tracks per event. This cut reduces the background from false K_s^0 pair candidates, removing only 7% of the DIS events.

The non-*ep* and photoproduction background in the selected sample was negligible. The data were not corrected for the biases introduced by the trigger requirements and selection cuts.

4. Selection of K_s^0-pair candidates

The K_s^0 meson candidates were reconstructed using tracks with at least 38 hits in the CTD and pseudorapidity within ± 1.75. The pseudorapidity cut and the required minimum number of hits ensured a good momentum resolution and a minimum transverse momentum of 0.1 GeV. In each event, oppositely charged track pairs assigned to a secondary vertex were combined to form K_s^0 candidates. Both tracks were assigned the mass of a charged pion and the invariant mass $M(\pi^+\pi^-)$ calculated. The secondary vertex resolution for these events, estimated using MC studies, is 2 mm in X and Y, and 4 mm in Z.

Additional requirements were applied to the selected K_s^0 candidates:

- $p_T(K_s^0) > 200$ MeV, for each K_s^0 candidate;
- $2 < d < 30$ cm, where d is the decay length of the K_s^0 candidate;
- $d_{XY} < 4$mm and $d_Z < 5.5$ mm, where d_{XY} and d_Z are, respectively, the projections on the XY plane and Z axis of the vector defined by the primary interaction point and the point of closest approach of the K_s^0 candidate;
- $\theta_{XY} < 0.12$, where θ_{XY} is the (collinearity) angle between the candidate K_s^0 momentum vector and the vector defined by the interaction point and the K_s^0 decay vertex in the XY plane;
- $p_T^A > 110$ MeV, for each K_s^0 candidate, where the Armenteros–Podolanski variable p_T^A is the projection of the candidate pion momentum onto a plane perpendicular to the K_s^0 candidate line of flight [18].

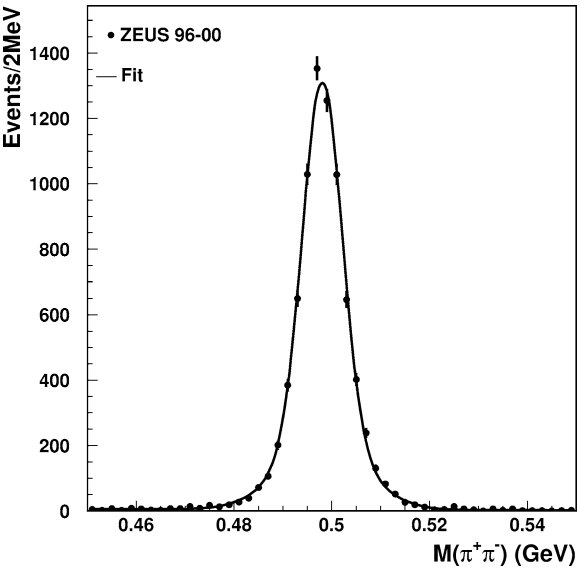

Fig. 1. The distribution of $\pi^+\pi^-$ invariant mass for events with at least two K_s^0 candidates passing all selection cuts. The solid line shows the result of a fit using one linear and two Gaussian functions.

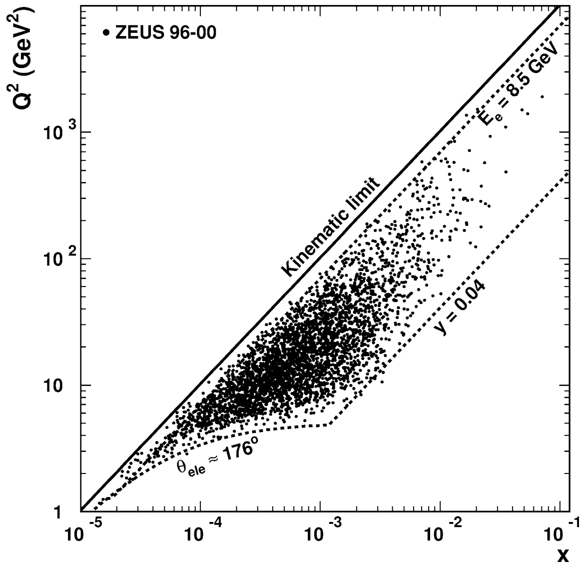

Fig. 2. The distribution in x and Q^2 of events passing all selection cuts. The dashed lines delineate approximately the kinematic region selected. The solid line indicates the kinematic limit for HERA running with 920 GeV protons.

The cuts on the decay length, distance of closest approach and collinearity angle significantly reduce the non-K_s^0 background as determined by Monte Carlo (MC) simulations. After the p_T^A cut, backgrounds from Λ, $\bar{\Lambda}$ and photon conversions are negligible. Only events with at least two selected K_s^0 candidates were kept for further analysis.

Fig. 1 shows the invariant mass distribution for K_s^0 candidates in the range $0.45 < M(\pi^+\pi^-) < 0.55$ GeV after the K_s^0-pair candidate selection. The distribution was fitted using one linear and two Gaussian functions. The linear function fits the background, one of the Gaussians fits the peak region in the central $\pi^+\pi^-$ invariant mass distribution, and the other Gaussian improves the fit at the tails. The two Gaussians were constrained to have the same mean value. A mass of 498 MeV and standard deviation width of 4 MeV were obtained from the fit with the central Gaussian, and a standard deviation width of 8.5 MeV was obtained from the fit with the other Gaussian. The normalization factor between the narrower and broader Gaussians is approximately 5.5. The invariant mass width is dominated by the momentum resolution of tracks reconstructed with the CTD. Only K_s^0 candidates in the region of ± 10 MeV around the fitted central mass were used to reconstruct the $K_s^0K_s^0$ invariant mass. High-statistics samples of Monte Carlo events, generated without resonances, were used to confirm that the event-selection criteria did not produce artificial peaks in the $K_s^0K_s^0$ invariant mass spectrum.

Fig. 2 shows the distribution in x and Q^2 of selected events containing at least one pair of K_s^0 candidates. The kinematic variables were reconstructed using the double angle method [19]. The virtual-photon proton centre-of-mass energy was in the range $50 < W < 250$ GeV.

5. Results

The $K_s^0K_s^0$ spectrum may have a strong enhancement near the $K_s^0K_s^0$ threshold due to the $f_0(980)/a_0(980)$ state [20,21]. Since the high $K_s^0K_s^0$ mass is the region of interest for this analysis, the complication due to the threshold region is avoided by imposing the cut $\cos\theta_{K_s^0K_s^0} < 0.92$, where $\theta_{K_s^0K_s^0}$ is the opening angle between the two K_s^0 candidates in the laboratory frame.

After applying all selections, 2553 K_s^0-pair candidates were found in the range $0.995 < M(K_s^0K_s^0) <$

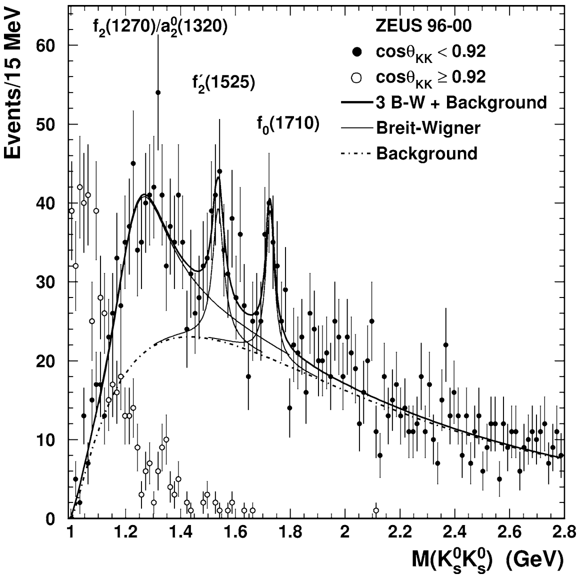

Fig. 3. The $K_s^0 K_s^0$ invariant mass spectrum for K_s^0 pair candidates with $cos\theta_{K_s^0 K_s^0} < 0.92$ (filled circles). The thick solid line is the result of a fit using three Breit–Wigners (thin solid lines) and a background function (dotted-dashed line). The K_s^0 pair candidates that fail the $cos\theta_{K_s^0 K_s^0} < 0.92$ cut are also shown (open circles).

2.795 GeV, where $M(K_s^0 K_s^0)$ was calculated using the K_s^0 mass of 497.672 MeV [4]. The momentum resolution of the CTD leads to an average $M(K_s^0 K_s^0)$ resolution which ranges from 7 MeV in the 1300 MeV mass region to 10 MeV in the 1700 MeV region. Fig. 3 shows the measured $K_s^0 K_s^0$ invariant mass spectrum. Two clear peaks are seen, one around 1500 MeV and the other around 1700 MeV, along with an enhancement around 1300 MeV. The data for $\cos\theta_{K_s^0 K_s^0} > 0.92$ are also shown. The mass scale uncertainties in the region of interest, arising from uncertainties in the magnetic field, is at the per mille level.

The distribution of Fig. 3 was fitted using three modified relativistic Breit–Wigner (MRBW) distributions and a background function $U(M)$;

$$F(M) = \sum_{i=1}^{3} \frac{m_{*,i} \Gamma_{d,i}}{(m_{*,i}^2 - M^2)^2 + m_{*,i}^2 \Gamma_{d,i}^2} + U(M), \quad (1)$$

where $\Gamma_{d,i}$ is the effective resonance width, which takes into account spin and large width effects [22], $m_{*,i}$ is the resonance mass, and M is $K_s^0 K_s^0$ invariant mass. The background function is

$$U(M) = A\left(M - 2m_{K_s^0}\right)^B \exp\left\{-C\sqrt{M - 2m_{K_s^0}}\right\}, \quad (2)$$

where A, B and C are free parameters and $m_{K_s^0}$ is the K_s^0 mass defined by Hagiwara et al. [4]. Monte Carlo studies showed that effects of the track-momentum resolution on the mass reconstruction were small compared to the measured widths of the states. Therefore, the resolution effects were ignored in the fit.

Below 1500 MeV, a region strongly affected by the $\cos\theta_{K_s^0 K_s^0}$ cut, a peak is seen around 1300 MeV where a contribution from $f_2(1270)/a_2^0(1320)$ is expected. This mass region was fitted with a single Breit–Wigner.

Above 1500 MeV, the lower-mass state has a fitted mass of 1537^{+9}_{-8} MeV and a width of 50^{+34}_{-22} MeV, in good agreement with the well established $f_2'(1525)$. The higher-mass state has a fitted mass of 1726 ± 7 MeV and a width of 38^{+20}_{-14} MeV. The widths reported here were stable, within statistical errors, to a wide variation of fitting methods including those using 30 MeV bins rather than the default 15 MeV bins. The width is narrower than the PDG value (125 ± 10 MeV) [4] reported for $f_0(1710)$, but when it is fixed to this value, the fit is still acceptable. For the purposes of the following discussion, this state is referred to as $f_0(1710)$.

The masses, widths and number of events from the fit with statistical errors are given in the top row of Table 1. It should be noted that there are correlations between the obtained parameters. In particular, the width and the number of events for each state are highly correlated. The mass spectrum is also consistent with the background function at higher masses, but masses above 2795 MeV were not included in the fit due to limited statistics. The sensitivity of the data to the widths of the resonances was studied. Several fits were performed fixing the width of the states $f_2'(1525)$ and $f_0(1710)$ to their PDG values; the results are shown in rows 2 to 4 of Table 1.

In the literature, there are several states reported in the mass region near 2000 MeV [4], namely, $f_2(1950)$ and $f_0(2020)$ which need confirmation, and $f_2(2010)$, $a_4(2040)$ and $f_4(2050)$ which have been confirmed. While no visible structure in this mass region exist in the data, these states may affect the background

Table 1
Normalized χ^2, masses in MeV, widths in MeV, and number of events extracted from the $K_s^0 K_s^0$ invariant mass fits (errors are statistical only). Widths reported without errors were fixed to the PDG values listed in the last row

Fit	χ^2/N	$f_2(1270)/a_2^0(1320)$			$f_2'(1525)$			$f_0(1710)$			$f_J(1980)$		
		mass	width	events	mass	width	events	mass	width	events	mass	width	events
1	0.97	1274^{+17}_{-16}	244^{+85}_{-58}	414^{+184}_{-125}	1537^{+9}_{-8}	50^{+34}_{-22}	84^{+41}_{-31}	1726 ± 7	38^{+20}_{-14}	74^{+29}_{-23}			
2	0.96	1272 ± 16	240^{+76}_{-55}	420^{+167}_{-122}	1539 ± 10	76	107 ± 30	1727 ± 7	39 ± 20	76^{+28}_{-24}			
3	1.02	1276 ± 16	258^{+80}_{-59}	480^{+190}_{-141}	1536 ± 8	49^{+30}_{-21}	85^{+38}_{-27}	1726 ± 13	125	122 ± 40			
4	1.02	1274 ± 15	251^{+72}_{-55}	476^{+176}_{-131}	1538 ± 10	76	108^{+31}_{-29}	1728 ± 13	125	120^{+41}_{-38}			
5	1.00	1283 ± 15	260^{+70}_{-55}	506^{+218}_{-122}	1540^{+12}_{-10}	70^{+43}_{-30}	116^{+59}_{-42}	1727 ± 7	47^{+23}_{-15}	91^{+34}_{-26}	1970^{+33}_{-45}	138^{+173}_{-89}	74 ± 40
Particle Data Group 2002 values (MeV) [4]													
		1275.5 ± 1.2, $185^{+3.4}_{-2.6}$ 1318 ± 0.6, 104.7 ± 1.9			1525 ± 5, 76 ± 10			1713 ± 6, 125 ± 10					

shape. The effect of the inclusion of a state in this region was examined, with the result shown in row 5 of Table 1. The description of the data between 1800 and 2000 MeV is improved with respect to the other fits. However, there is no improvement in the overall χ^2/dof.

The $K_s^0 K_s^0$ spectrum after all cuts was also fitted with the background function only. The fit can be rejected with a 99.4% confidence level using a simple χ^2 test over the mass region 1000 to 2800 MeV.

It was found that 93% of the K_s^0-pair candidates selected within the detector and trigger acceptance are in the target region of the Breit frame [23], the hemisphere containing the proton remnant. Of the K_s^0-pair candidates in the target region, 78% are in the region $x_p = 2p_B/Q > 1$, where p_B is the absolute momentum of the $K_s^0 K_s^0$ in the Breit frame. High x_p corresponds to production of the K_s^0-pair in a region where sizeable initial state gluon radiation may be expected. This is in contrast to the situation at e^+e^- colliders where the particles entering the hard scattering are colourless.

6. Conclusions

The first observation in *ep* deep inelastic scattering of a state at 1537 MeV, consistent with $f_2'(1525)$, and another at 1726 MeV, close to $f_0(1710)$, is reported. There is also an enhancement near 1300 MeV which may arise from the production of $f_2(1270)$ and/or $a_2^0(1320)$ states. The width of the state at 1537 MeV is consistent with the PDG value for the $f_2'(1525)$. The state at 1726 MeV has a mass consistent with the glueball candidate $f_0(1710)$, and is found in a gluon-rich region of phase space. However, it's width of 38^{+20}_{-14} MeV is narrower than the PDG value of 125 ± 10 MeV for the $f_0(1710)$.

Acknowledgements

We thank the DESY directorate for their strong support and encouragement. The special efforts of the HERA machine group in the collection of the data used in this Letter are gratefully acknowledged. We are grateful for the support of the DESY computing and network services. The design, construction and installation of the ZEUS detector have been made possible by the ingenuity and effort of many people from DESY and home institutes who are not listed as authors. We also thank F. Close, S. Godfrey and H. Lipkin for their valuable comments and advice.

References

[1] S. Godfrey, J. Napolitano, Rev. Mod. Phys. 71 (1999) 1411.
[2] E. Klempt, in: Proc. of the PSI Zuoz Summer School on Phenomenology of Gauge Interactions, 2000, p. 61, hep-ex/0101031.
[3] C.J. Morningstar, M. Peardon, Phys. Rev. D 60 (1999) 034509; C. Michael, M. Teper, Nucl. Phys. B 314 (1989) 347.
[4] Particle Data Group, K. Hagiwara, et al., Phys. Rev. D 66 (2002) 1.
[5] BES Collaboration, J.Z. Bai, et al., Phys. Rev. Lett. 77 (1996) 3959.
[6] WA102 Collaboration, D. Barberis, et al., Phys. Lett. B 453 (1999) 305.
[7] L3 Collaboration, M. Acciari, et al., Phys. Lett. B 501 (2001) 173.
[8] ZEUS Collaboration, M. Derrick, et al., Z. Phys. C 68 (1995) 29;
ZEUS Collaboration, J. Breitweg, et al., Eur. Phys. J. C 2 (1998) 77.
[9] H1 Collaboration, S. Aid, et al., Nucl. Phys. B 480 (1996) 3; H1 Collaboration, C. Adloff, et al., Z. Phys. C 76 (1997) 213.
[10] ZEUS Collaboration, U. Holm (Ed.), The ZEUS Detector. Status Report (unpublished), DESY (1993), available on http://www-zeus.desy.de/bluebook/bluebook.html.
[11] N. Harnew, et al., Nucl. Instrum. Methods A 279 (1989) 290; B. Foster, et al., Nucl. Phys. B (Proc. Suppl.) 32 (1993) 181; B. Foster, et al., Nucl. Instrum. Methods A 338 (1994) 254.
[12] M. Derrick, et al., Nucl. Instrum. Methods A 309 (1991) 77; A. Andresen, et al., Nucl. Instrum. Methods A 309 (1991) 101; A. Caldwell, et al., Nucl. Instrum. Methods A 321 (1992) 356; A. Bernstein, et al., Nucl. Instrum. Methods A 336 (1993) 23.
[13] A. Bamberger, et al., Nucl. Instrum. Methods A 401 (1997) 63.
[14] ZEUS Collaboration, S. Chekanov, et al., Eur. Phys. J. C 21 (2001) 443.
[15] A. Bamberger, et al., Nucl. Instrum. Methods A 382 (1996) 419.
[16] S. Catani, et al., Nucl. Phys. B 406 (1993) 187.
[17] F. Jacquet, A. Blondel, in: Proc. of the Study for an ep Facility for Europe, Hamburg, Germany, 1979, p. 391.
[18] J. Podolanski, R. Armenteros, Philos. Mag. 45 (1954) 13.
[19] S. Bentvelsen, J. Engelen and P. Kooijman, in: Proc. of the Workshop on Physics at HERA, Hamburg, Germany, DESY, 1992, Vol. 1, p. 23..
[20] S. Godfrey, N. Isgur, Phys. Rev. D 32 (1985) 189.
[21] WA102 Collaboration, D. Barberis, et al., Phys. Lett. B 489 (2000) 24;
T. Barnes, IX International Conference on Hadron Spectroscopy, Protvino, Russia, AIP Conf. Proc. 619 (2002) 447, hep-ph/0202157.
[22] J. Benecke, H.P. Dürr, Nuovo Cimento 56 (1968) 269.
[23] R.P. Feynman, Photon–Hadron Interactions, Benjamin, New York, 1972;
K.H. Streng, T.F. Walsh, P.M. Zerwas, Z. Phys. C 2 (1979) 237.