Partial Wave Analysis of the Centrally Produced $K_S K_S$ System at 800 GeV/c

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Results are presented from a partial wave analysis of a sample of centrally produced mesons in the reaction $pp \to p_{\rm slow}(K_S K_S)p_{\rm fast}$, with 800 GeV/$c$ protons incident on a liquid hydrogen target. The meson system is found to be predominantly S wave in the mass range between $K_S K_S$ threshold and 1.55 GeV/c^2. The $f_0(1500)$ is observed in this region. Above 1.55 GeV/c^2 two solutions are possible, one with mainly S wave and another with mainly D wave. This ambiguity prevents a unique determination of the spin of the $f_J(1710)$ meson. [S0031-9007(98)07609-1]

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Significant theoretical progress has been made recently with two separate lattice gauge calculations of the lowest lying scalar glueball [1]. The two calculated masses are 1550 ± 95 MeV/c^2 and 1740 ± 71 MeV/c^2. The leading experimental candidates are the $f_0(1500)$ and the $f_J(1710)$. The $f_0(1500)$ was first observed in $\pi^- p$ interactions [2]. Its existence was beautifully confirmed, and several decay branching ratios were measured by the Crystal Barrel Collaboration [3]. Amsler and Close [4] have pointed out that the values of these branching ratios make it unlikely that the $f_0(1500)$ is a $q\bar{q}$ meson. If the $f_0(1500)$ is a glueball, then its production may be favored in doubly diffractive hadronic interactions. In this paper, we report the observation of the $f_0(1500)$ in central production in the doubly diffractive reaction,

$$pp \to p_{\rm slow}(K_S K_S)p_{\rm fast}, \qquad K_S \to \pi^+\pi^-. \tag{1}$$

The advantage of the $K_S K_S$ system over K^+K^- is that for two identical bosons only states with $J^{PC} = (\text{even})^{++}$ are allowed.

The results presented here are based on an analysis of 10% of the 5×10^9 events recorded by Fermilab E690 during Fermilab's 1991 fixed target run. The E690 apparatus consisted of a high rate, open geometry multiparticle spectrometer (Fig. 1) used to measure the target system (T) in $pp \to p_{\rm fast}(T)$ reactions, and a beam spectrometer system used to measure the incident 800 GeV/c beam and scattered proton. A liquid hydrogen target was located just upstream of the multiparticle spectrometer. The target was surrounded by a segmented lead-scintillator "veto counter," which was used to detect the presence of charged or neutral particles outside the aperture of the multiparticle spectrometer [5].

Final state (1) was selected by requiring a primary vertex in the LH_2 target with two K_S, an incoming beam track, and a fast forward proton. No direct measurement was made of the slow proton $p_{\rm slow}$, and no direct particle identification was used. The target veto system was used to reject events with more than a missing proton. Events were accepted when no veto counter was on, or only one veto counter was on, and the missing p_t pointed to it.

The missing mass squared seen in Fig. 2a shows a clear proton peak with little background. Figure 2b shows the uncorrected x_F distribution for the $K_S K_S$ system. The distribution is not symmetric about $x_F = 0$ because the detection efficiency and momentum resolution of the multiparticle spectrometer decreased rapidly for high energy particles produced in the forward direction in the pp center of mass system. Figure 2c shows the $\pi^+\pi^-$ invariant mass distribution; the arrows indicate the cuts used. In all plots the selected events are shaded. With this selection, the minimum rapidity gap between $p_{\rm slow}$ and the $K_S K_S$ system is 1.2 units. The rapidity gap between the meson system and $p_{\rm fast}$ is greater than 3.7 units for all events.

In the selected events, the three momentum of $p_{\rm slow}$ and the longitudinal momentum of $p_{\rm fast}$ were calculated

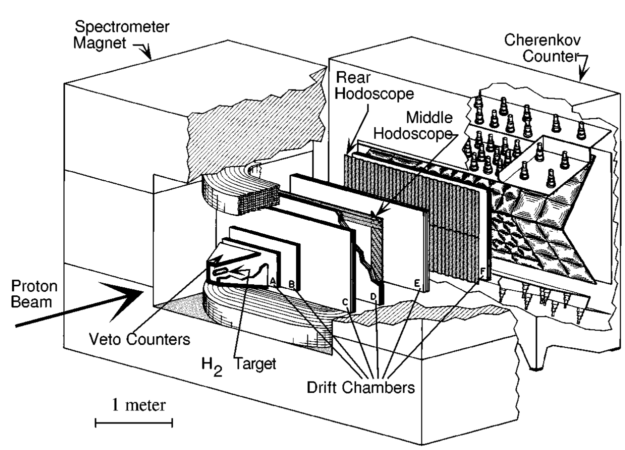

FIG. 1. E690 multiparticle spectrometer.

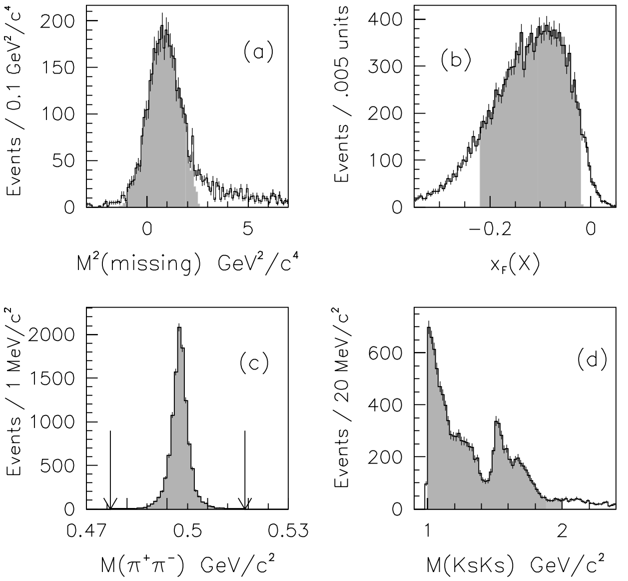

FIG. 2. (a) Missing mass squared for $1.4 < M(K_S K_S) < 1.8\ \mathrm{GeV}/c^2$. (b) Uncorrected x_F distribution. (c),(d) Measured $\pi^+\pi^-$ and $K_S K_S$ invariant masses.

using energy and momentum conservation, assuming that the unmeasured object had the proton mass.

Figure 2d shows the $K_S K_S$ invariant mass for the events that passed the previous cuts. The current analysis was performed using 11 182 events with $K_S K_S$ mass between 1 and $2\ \mathrm{GeV}/c^2$. The analysis was not continued to a higher mass because the number of events is very low; but for $-0.22 < x_F < -0.02$ the $K_S K_S$ invariant mass beyond $2\ \mathrm{GeV}/c^2$ is smooth with no evidence of the narrow $f_J(2220)$ state seen by the BES Collaboration [2,6].

The reaction studied here was analyzed as a two step process: the production step in which an (X) system is formed by the collision of two objects (from now on referred to as Pomerons) emitted by the scattered protons, and the decay step in which (X) decays into $K_S K_S$. The production coordinate system was defined in the (X) system center of mass, with the y axis perpendicular to the plane of the two Pomerons in the pp center of mass, and the z axis in the direction of the beam Pomeron in the (X) center of mass. The two variables needed to specify the decay process were taken as the polar and azimuthal angles (θ, ϕ) of one of the K_S (taken at random) in the production coordinate system. The acceptance corrected $\cos\theta$ and ϕ distributions are shown in Figs. 3 and 4. The acceptance is flat in ϕ and dips near $\cos\theta = \pm 1$. The solid lines represent the angular distributions obtained from the wave amplitudes of Fig. 7. These distributions are different from the ones observed in the reaction $pp \to p_S(K^+K^-)p_f$ by WA76 [7]. While their distributions are strongly peaked at $\cos\theta = \pm 1$ in the mass region above $1.48\ \mathrm{GeV}/c^2$ (consistent with $J = 2$, $m = 0$), ours are fairly flat.

The five variables used to specify the production process were the transverse momenta squared of the slow and fast protons $(p_{t,s}^2, p_{t,f}^2)$, the x_F and invariant mass of the $K_S K_S$ system, and δ, the angle between the planes of the scattered protons in the $K_S K_S$ center of mass. Although our 11 182 events constitute a large sample, it is not large enough to bin the data in all five production variables. The analysis was done in bins of the $K_S K_S$ invariant mass for the selected region in x_F, integrating over $p_{t,s}^2$, $p_{t,f}^2$ and δ.

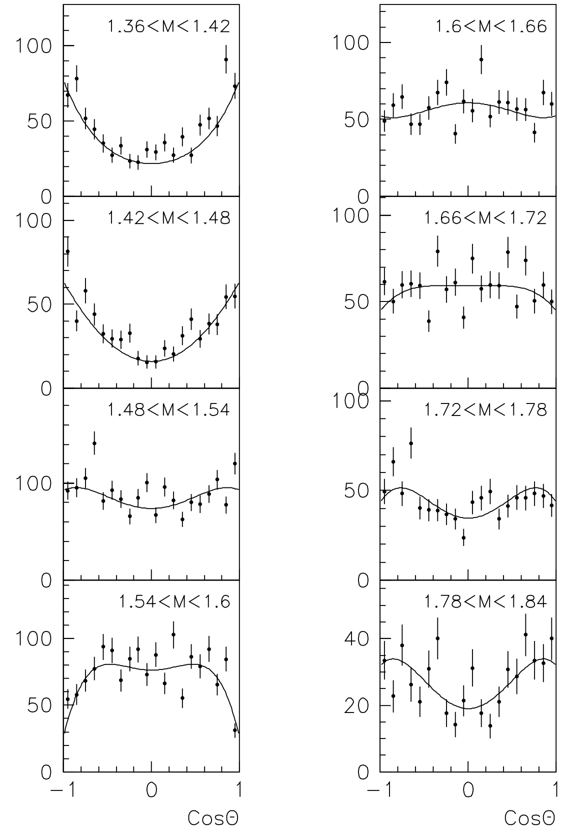

FIG. 3. Acceptance corrected $\cos\theta$ angular distributions in bins of the $K_S K_S$ invariant mass M, starting at $1.36\ \mathrm{GeV}/c^2$ in steps of $60\ \mathrm{MeV}/c^2$. The curves are explained in the text.

The acceptance corrected moments, defined by

$$I(\Omega) = \frac{1}{\sqrt{4\pi}}\left\{\sum_l t_{l0} Y_l^0 + 2\sum_{l,m>0} t_{lm}\mathrm{Re}(Y_l^m)\right\} \qquad (2)$$

are shown in Fig. 5, together with the measured mass distribution. The odd moments (not shown) are consistent with zero, as expected for a system of two identical bosons. The t_{00} moment is the acceptance corrected mass distribution. The error bars are statistical errors only.

In the two step process considered here, the (X) system is formed by the interchange of two Pomerons, whose momentum vectors lie in a plane in the pp center of mass system. Parity conservation in the strong interactions implies that reflection in this plane should be a symmetry of the system [8]. Therefore the amplitudes used for the partial wave analysis were defined in the reflectivity basis [9]. Since the t_{43} and t_{44} moments are consistent with zero (see Fig. 5), only spherical harmonics with $l = 0, 2$

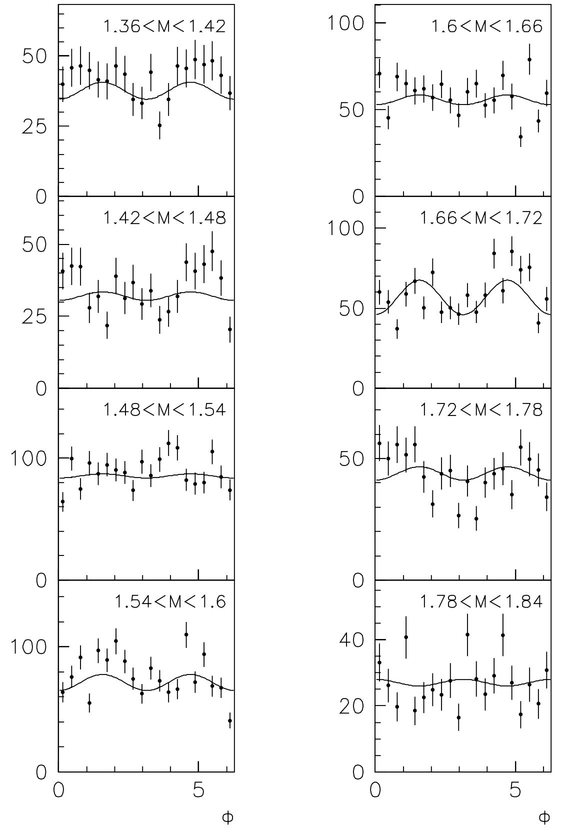

FIG. 4. Acceptance corrected ϕ angular distributions in bins of the $K_S K_S$ invariant mass M, starting at 1.36 GeV/c^2 in steps of 60 MeV/c^2. The curves are explained in the text.

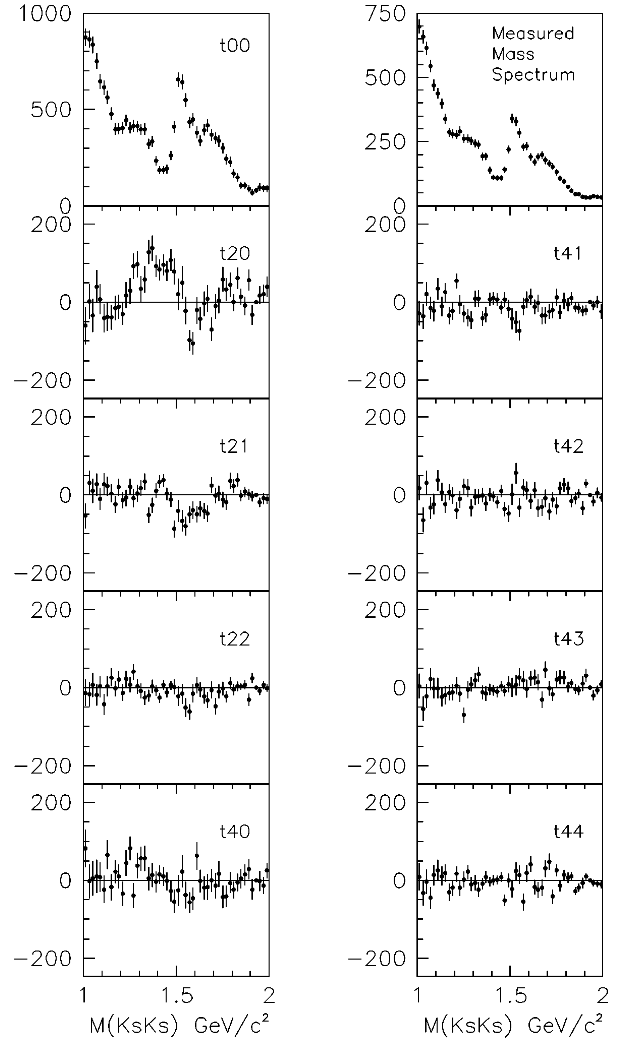

FIG. 5. Uncorrected mass distribution and acceptance corrected moments as a function of the $K_S K_S$ invariant mass.

and $m = 0, \pm 1$ were considered. The waves used were L_m^ϵ, with $L = S, D$, $m \geq 0$, and reflectivity $\epsilon = \pm 1$,

$$S_0^- = Y_0^0 = 1/\sqrt{4\pi}\,, \tag{3}$$

$$D_0^- = Y_2^0 = \sqrt{5/16\pi}\,(3\cos^2\theta - 1)\,, \tag{4}$$

$$D_1^- = (Y_2^1 - Y_2^{-1})/\sqrt{2} = -\sqrt{15/16\pi}\,\sin 2\theta \cos\phi\,, \tag{5}$$

$$D_1^+ = (Y_2^1 + Y_2^{-1})/\sqrt{2} = -i\sqrt{15/16\pi}\,\sin 2\theta \sin\phi\,. \tag{6}$$

Waves with different reflectivity do not interfere.

The partial wave analysis was done in two different ways. First, the amplitudes were extracted from the moments shown in Fig. 5. Second, the amplitudes were determined by maximizing the extended likelihood with respect to the four wave moduli and the two relative phases $\varphi(D_{0,1}^-) - \varphi(S_0^-)$. Within errors both analyses gave the same answer. The programs were tested using Monte Carlo events generated with interfering S and D waves.

When using four waves the inherent ambiguities of a two-body system are such that there are two solutions for each mass bin, one for each of the combinations of the two complex Barrelet zeros Z_1 and Z_2 [8,10]. Both solutions give identical moments or identical values of the likelihood. In order to continue the solutions from one mass bin to the next, one follows the Barrelet zeros or the solutions themselves. When a zero crosses the real axis the solutions bifurcate. The imaginary parts of Z_1 and Z_2 are shown in Figs. 6a and 6b. Z_1 becomes real at 1.55 GeV/c^2. At this mass bin and the following one, both solutions collapse into one, as can be seen in Figs. 6c and 6d. Before this bifurcation point there are two solutions (Figs. 6c and 6d), one which is mostly S wave (in red), and another that is mostly D wave (in blue). At threshold the $K_S K_S$ cross section is dominated by the presence of the $f_0(980)$ [11]; therefore, it is possible to eliminate the solution that has a very small S wave contribution at threshold. The remaining solution (the "allowed" solution) bifurcates at 1.55 GeV/c^2 into a solution that is mostly S wave, and another that is mostly D wave. Before the bifurcation point the allowed solution uses the Z_1 Z_2 combination of zeros. After the bifurcation point, one solution uses the combination Z_1 Z_2 (Fig. 7 left),

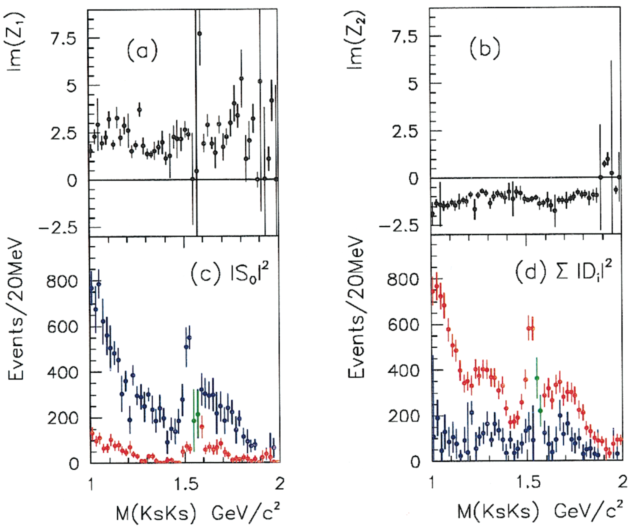

FIG. 6(color). (a),(b) Imaginary parts of Z_1 and Z_2. (c) S and (d) total D waves, for the two (red and blue) solutions in each mass bin. For mass bins where the solutions are identical the points are green.

and the other the combination $Z_1\ Z_2^*$ (Fig. 7 right). The results in these figures were obtained using the maximum likelihood method; the errors are statistical errors only.

A striking feature of the allowed solution is the large S wave peak observed at 1.52 GeV$/c^2$. The difference between this value and the $f_0(1500)$ mass of 1.50 GeV$/c^2$ determined by the Crystal Barrel Collaboration [3] could be due to interference with the S wave background. Beyond 1.55 GeV$/c^2$ both solutions are equally valid. The ambiguity above 1.55 GeV$/c^2$ prevents a unique determination of the spin of the $f_J(1710)$ meson.

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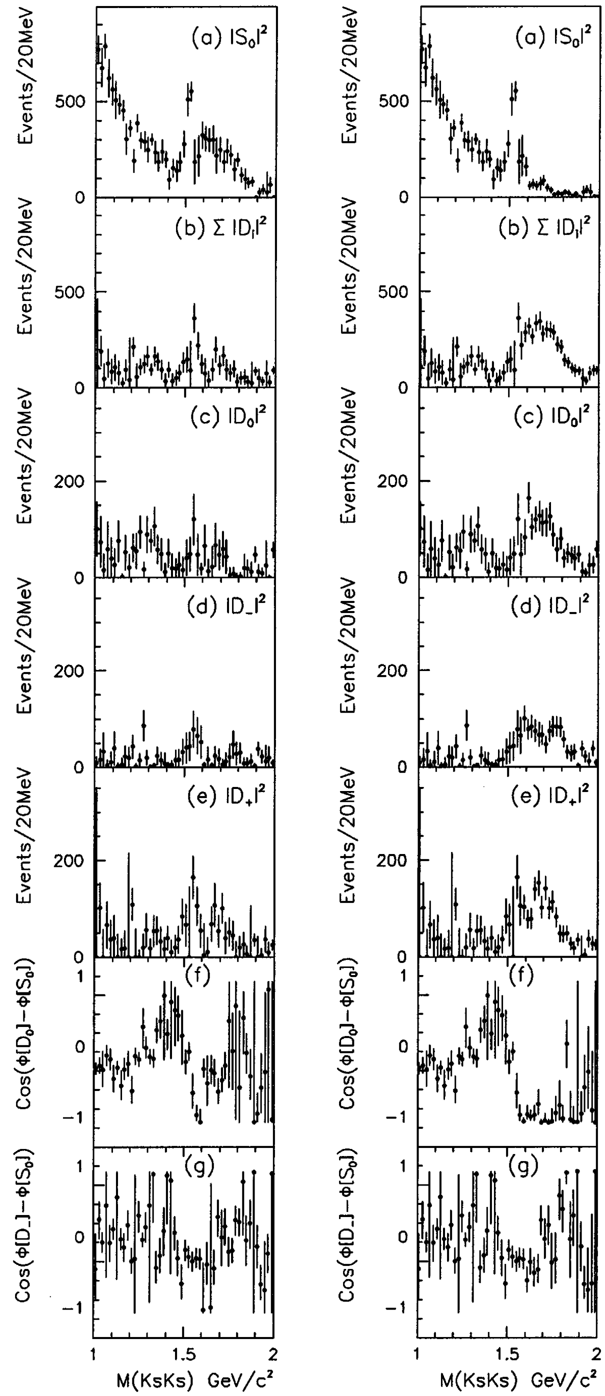

FIG. 7. Waves as a function of $K_S K_S$ invariant mass for solutions 1 (left) and 2 (right). (a) S and (b) total D waves, (c) to (e) individual D wave, and (f) and (g) phases relative to the S wave.