Observation of $f_0(1500)$ decay into $K_L K_L$

Crystal Barrel Collaboration

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Abstract: The $f_0(1500)$ is observed in its $K\overline{K}$ decay mode in an amplitude analysis of high statistics data in $\overline{p}p$ annihilation at rest into $\pi^0 K_L K_L$. The mass and width is found to be $(m, \Gamma) = (1515 \pm 20, 105 \pm 15)$ MeV. A comparison of the decay rate into $2\pi^0$ shows that this state cannot be dominantly $s\overline{s}$. The $f_2'(1525)$ has been observed for the first time in $\overline{p}p$ annihilation and its production rate is consistent with the expectation from the OZI rule.

We have reported the observation of a new

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isoscalar scalar resonance, the $f_0(1500)$, decaying into $\pi^0\pi^0$ [1,2] , $\eta\eta$ [3] and $\eta\eta'$ [4] in $\overline{p}p$ annihilation at rest into three pseudoscalar mesons. The average mass and width are 1509 ± 10 and 116 ± 17 MeV, respectively. A coupled channel analysis of the final states $3\pi^0$ [1], $\pi^0\eta\eta$ [3] and $\pi^0\pi^0\eta$ [5] has also been performed, leading to consistent mass and width of 1500 ± 10 and 154 ± 30 MeV, respectively [6]. The $f_0(1500)$ decay into $4\pi^0$ has also been reported by our collaboration [7].

The decay branching ratio of $f_0(1500)$ to $K\overline{K}$ is an important ingredient to understand the nature of this state since it has been interpreted in ref. [8] as the ground state scalar glueball predicted by lattice gauge theories due to the absence of signal in $K\overline{K}$ from earlier bubble chamber experiments [9].

In this letter we present an analysis of the reaction $\overline{p}p\to\pi^0K_LK_L$ at rest with high statistics. We report the observation of $f_0(1500)$ in its $K\overline{K}$ decay mode and determine its coupling to $K\overline{K}$.

The experiment was performed at the Low Energy Antiproton Ring (LEAR) at CERN. Antiprotons with a momentum of 200 MeV/c are stopped in a liquid hydrogen target. The target is surrounded by two cylindrical proportional wire chambers, a jet drift chamber to detect charged particles and a barrel-shaped calorimeter consisting of 1380 CsI(Tl) crystals with photodiode readout. The assembly is located in a solenoid providing a homogeneous field of 1.5 T parallel to the incident antiproton beam. A detailed description of the apparatus can be found in ref. [10].

The present analysis is based on 13.2 million events involving only neutral particles which have been taken by vetoing charged particles with the proportional wire chambers. Using the ratio $(3.9\pm0.3)\%$ of all-neutral (0-prong) events to the number of stopped antiprotons [11], this data sample corresponds to $(3.38\pm0.26)\times10^8$ $\overline{p}p$ annihilations.

In contrast to the other hadrons detected with the Crystal Barrel, K_L have a relatively long lifetime. For a typical momentum of 400 MeV/c about 96% of the K_L reach the calorimeter where they may interact hadronically. The interaction probability in CsI was measured earlier [12] at 795 MeV/c, $(57\pm3\%)$, using $\overline{p}p\to K_SK_L$. The K_L-interaction leads to one or several clusters of energy deposit in the crystals (PED). The probability for one PED is typically 28% [12]. For a K_L with one PED, the PED location is close to the impact point. This correlation can be used in $\pi^0K_LK_L$ to identify the direction of an interacting K_L with the one of the PED.

Annihilations into $\pi^0K_LK_L$ were selected by 3-PED events, where two PEDs belong to the π^0decaying to two photons and one PED to an interacting K_L. The second K_L is not interacting and hence missing. The measurement of the momentum of the π^0 and of the direction of the interacting K_L are sufficient to reconstruct the kinematics of the full event, i.e. the energies of both K_L and the direction of the missing K_L.

The all-neutral data sample is reduced to 158,413 events when requiring 3 PEDs, each with at least 20 MeV energy deposit. The mass resolution of the π^0 is $\sigma=7.5$ MeV and events with one π^0 and one PED are pre-selected by requiring at least one PED-PED invariant mass combination within $\pm$ 30 MeV of the nominal π^0 mass. From at most three possible combinations, the correct one is assumed to be the one closest to the π^0 mass. A cut is then applied to remove events for which one PED is identified as a small shower fluctuation. This leaves 90,728 π^0+1 PED events.

Since the interacting K_L typically does not deposit all its energy, the total measured momentum p_{tot} is related to the total measured energy E_{tot} by

$$p_{tot} \quad \leq \quad \sqrt{(2m_p-E_{tot})^2-m_K^2}, \qquad (1)$$

which is fulfilled for 60,983 events.

The π^0 mass window is then reduced to within $\pm$ 15 MeV of the nominal π^0 mass and events with at least one PED-PED invariant mass in this window are considered as events with a real π^0 (51,954 events). Events with no entries in this window but at least one entry in either of the side-bins (9,029 events) are used to describe the background under the π^0 peak.

To obtain a sharp boundary for the $\pi^0K_LK_L$ Dalitz plot we use the nominal π^0 mass and recalculate the energy of the π^0, using the measured photon momenta. The resulting systematic error is small, the difference between the calculated and directly measured π^0 energy being smaller than the π^0 energy resolution.

By requiring the π^0 momentum to be smaller than 666 MeV/c, the maximum momentum of the π^0 in $\overline{p}p \to \pi^0 K_L K_L$, 50,064 [8,622] events are selected. The first number refers to the number of events in the π^0 mass window and the number in brackets to the number of events in the side-bins.

The angle θ of the interacting K_L with respect to the π^0 momentum is transformed into θ^*, the corresponding angle in the rest frame of the $K_L K_L$ system, to calculate the laboratory momenta of both K_L and the direction of the missing K_L. An ambiguity occurs when both K_L are boosted in the forward direction (when $m(K_L K_L) < 1125$ MeV) in which case it is not possible to determine whether the detected K_L is emitted in the forward or in the backward direction in the $K\overline{K}$ rest frame. In this case we use the probability distribution $d\cos\theta^*/d\cos\theta$ to choose between the two solutions. However, 1,071 [308] events cannot be reconstructed either due to (background) events not matching the kinematics for $\pi^0 K_L K_L$ or due to the finite experimental resolution around the maximum angle of the interacting K_L in the laboratory frame. The latter reduces the reconstruction efficiency and leads to a narrow region of low intensity in the $\pi^0 K_L K_L$ Dalitz plot at low $K_L K_L$ masses (see fig 1 below). The full kinematical reconstruction leads to a sample of 48,993 [8,314] $\pi^0 K_L K_L$ events.

The main background contributions are due to the annihilation channels $\overline{p}p \to \omega K_L K_L$ where ω decays to $\pi^0\gamma$ and both K_L are missing, and $\overline{p}p \to K_S K_L$ where one photon from $K_S \to \pi^0\pi^0 \to 4\gamma$ and the K_L are undetected. These events are associated with a prominent ω or K_S peak in the 3 PED invariant mass distribution and can be removed with appropriate mass cuts without cutting into the $\pi^0 K_L K_L$ phase space. This leaves 45,153 events in the π^0 mass window and 7,795 events in the π^0 side-bins.

The Dalitz plots from the π^0 side-bins are now subtracted leading to $(3.74 \pm 0.16) \times 10^4$ $\pi^0 K_L K_L$ events where the error includes systematic uncertainties in the estimate of the background from the side-bins.

Residual background from $\omega K_L K_L$ and $K_S K_L$ and contributions from final states like $\omega\pi^0$, $\omega\eta$, $3\pi^0$ and $\pi^0\pi^0\eta$ were studied by Monte Carlo simulation. The total residual background contamination in the background subtracted $\pi^0 K_L K_L$ Dalitz plot is $(3.4 \pm 0.5)\%$ [13]. This background is small and no statistically significant contribution to any specific region in the $\pi^0 K_L K_L$ Dalitz plot was found.

The acceptance for $\pi^0 K_L K_L$ events has been calculated separately for the π^0 and the K_L's. For the latter GEANT [14] simulation does not give a correct description of the K_L interaction probability at low momenta. Hence, we extracted the interaction probability directly from the $\pi^0 K_L K_L$ data. We compare the momentum distributions of the two K_L in a $\pi^0 K_L$ mass window of ± 20 MeV around the nominal K^* mass which covers the full momentum range. Together with the acceptance for the π^0 obtained by Monte Carlo simulation, the $\pi^0 K_L K_L$ data are then corrected with the resulting acceptance. The acceptance is slowly varying over the Dalitz plot.

We cannot determine the branching ratio of $\overline{p}p \to \pi^0 K_L K_L$ accurately from our data due to the uncertainty in the absolute K_L detection efficiency. Instead, we will use the average value of $(7.5 \pm 0.3) \times 10^{-4}$ for $\pi^0 K_S K_S$ from ref. [26] and ref. [27].

The background-subtracted and acceptance corrected Dalitz plot is shown in fig. 1. The $K^{*0}(896)$ are clearly observed as two perpendicular bands in the lower left region of the Dalitz plot. These bands are expected to display a decay angular distribution $\sim \cos^2\theta$ (from the ${}^1S_0$ $\overline{p}p$ initial state) but are affected by large interference effects with other resonances. Apart from the $K^*(896)$ bands, one sees clear structures along constant $K\overline{K}$ invariant masses, indicating the presence of resonances in the $K\overline{K}$ system in the 1300-1500 MeV mass region like $f_2(1270)/a_2(1320)$ and $f_0(1370)/a_0(1450)$ decaying to $K\overline{K}$. The scalar resonances are expected in the central region of the plot. Note also the enhancements near the K^* bands at the boundary of the Dalitz plot corresponding to a $K\overline{K}$ mass of about 1520 MeV where the $f_2'(1525)$ is expected. The absence of a clear threshold enhancement in $K^0\overline{K^0}$ due to $f_0(980)/a_0(980)$ has already been

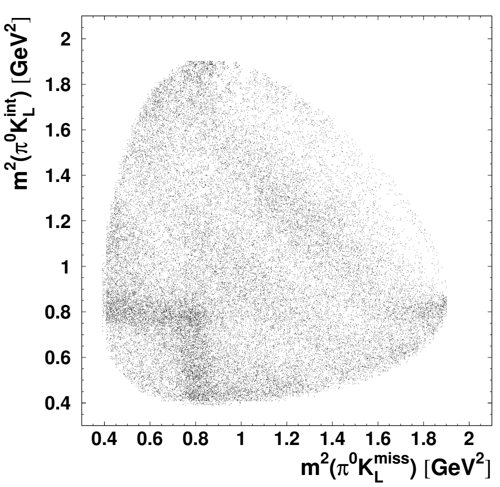

Fig. 1. $\pi^0 K_L K_L$ Dalitz plot. At low $K\overline{K}$ masses the reduced reconstruction efficiency around the maximum decay angle of the interacting K_L is seen as a narrow region of low intensity.

noted in ref. [15].

The $\pi^0 K_L K_L$ data are analyzed in the helicity formalism [16] in terms of the isobar model [17], in which the $\overline{p}p$ system is assumed to decay to the three-body final state $\pi^0 K_L K_L$ through two-body intermediate states. We assume dominance of annihilation from $\overline{p}p$ S-states in liquid hydrogen [18]. Hence only the ${}^1S_0(J^{PC}=0^{-+})$ initial state contributes to $\pi^0 K_L K_L$. For details of the Dalitz plot analysis procedure, see for instance ref. [19]. An exploratory partial wave analysis of $\pi^0 K_L K_L$ used Breit-Wigner amplitudes for all resonances [20]. Now, to conserve unitarity for intermediate resonances with the same quantum numbers, we replace here the Breit-Wigner amplitudes of ref. [19] by the dynamical functions [21]

$$\hat{F} \quad = \quad (I - i\rho\hat{K})^{-1}\hat{P}, \tag{2}$$

where the K-matrix is defined as a sum of poles describing all contributing resonances:

$$\hat{K}_{ij} \quad = \quad \sum_{\alpha} \frac{g_{\alpha i} g_{\alpha j}}{m_\alpha^2 - m^2} \, \frac{B_L(q_i)}{B_L(q_{\alpha i})} \, \frac{B_L(q_j)}{B_L(q_{\alpha j})}. \tag{3}$$

The couplings g_{α_i} are related to the partial widths $\Gamma_{\alpha i}$ via

$$g_{\alpha i}^2 \quad = \quad \frac{m_\alpha \Gamma_{\alpha i}}{\rho_i(m_\alpha)}, \tag{4}$$

where $\rho_i = 2q_i/m$ is the dimensionless two-body phase space factor for the decay into a particular channel i. The factors $B_L(q)$ are the Blatt-Weisskopf damping factors [19,22]. The total width Γ_α is the sum of the partial widths divided by phase space $\Gamma_{\alpha i}/\rho_{\alpha i}$.

The expression for the production vector $\hat{P}$ is the same as for the K-matrix in eqn. (3) but the couplings $g_{\alpha i}$ to the initial channels are replaced by a complex coupling β_α^0 to the annihilation vertex of the $\overline{p}p$ system:

$$\beta_\alpha^0 \quad = \beta_\alpha \sqrt{\textstyle\sum_i g_{\alpha i}^2} \, . \tag{5}$$

The $\pi^0 K_L K_L$ Dalitz plot is fitted using the χ^2 minimization method based on the MINUIT [23] program package. The χ^2 sum extends over all bins in the background subtracted and acceptance corrected $\pi^0 K_L K_L$ Dalitz plot. The Dalitz plot is divided into bins of size corresponding to twice the experimental resolution. The bin spacing is 0.05 GeV^2 for a total of 882 bins. Bins at the boundary of the $\pi^0 K_L K_L$ Dalitz plot are not considered in the fit and this reduces the number of bins to 797. The $\pi^0 K_L K_L$ Dalitz plot has not been symmetrized with respect to the two K_L due to their different systematics in the detection and reconstruction. A χ^2 test of pairs of symmetric bins is performed. Pairs of bins with number of entries differing by more than 3σ are found only around the maximum laboratory decay angle of the interacting K_L. Since this is due to the reduced reconstruction efficiency we do not consider these bins in the fit. This leaves 788 bins for the partial wave analysis.

The total transition amplitude for bin i is given by the sum of contributions $\alpha_l A_{li}$ where A_{li} is the amplitude for a given chain l of intermediate resonances and $\alpha_l = a_l \exp(i\phi)$ is determined by the fit. The A_{li} are normalized to the number of observed $\pi^0 K_L K_L$ events so that a_l^2 gives the fractional contribution of chain l to $\pi^0 K_L K_L$ in the absence of interferences between the various chains. Hence, in general, $\sum_l a_l^2$ is not equal to one. Note that the amplitudes β_α^0 refer to the relative production strength of resonances within a partial wave of the same quantum numbers whereas α_l gives the overall production amplitude.

We now describe the first attempt to fit the

Dalitz plot (fig. 1), introducing all the well established resonances which may contribute to $\pi^0 K_L K_L$: $K^*(896)$ and $K_0^*(1430)$ decaying to $K\pi$, $f_2(1270)$, $a_2(1320)$ and $f_2'(1525)$ decaying to $K\overline{K}$. To describe the $K\overline{K}$ mass distribution, in particular the central peak around 1400 MeV in fig. 2, we introduce in addition a $K\overline{K}$ S-wave parametrized by a (1×1) K-matrix with one pole, hence a Breit-Wigner amplitude. Both isospins $I = 0$ and $I = 1$ for the $K\overline{K}$ S-wave are possible. The $f_0(980)/a_0(980)$ also decaying to $K\overline{K}$ are not considered at this point.

The self-interference between the two neutral K^* bands is constructive and independent of the isospin of the initial $\overline{p}p$ state. The relative phase ϕ between the two amplitudes is therefore fixed to zero. The K^* mass and width (broadened by the experimental resolution) are left free in the fit. The relative phase between the amplitudes for the $K\pi$ S-wave is also fixed to $\phi_{(K\pi)_S} = 0$.

For the $f_2(1270)$, $a_2(1320)$ and $f_2'(1525)$ we use relativistic Breit-Wigner amplitudes [19], equivalent to a production amplitude $\hat{F}$ with one resonance pole and a coupling to one decay channel. Masses and widths of $f_2(1270)$ and $a_2(1320)$ cannot be determined due to interference and are therefore fixed to the standard values [24]. The mass and width of $f_2'(1525)$ are left as free parameters.

For the $(K\pi)$ S-wave we determine the parameters of the K-matrix by fitting the phase shifts from ref. [25] to the scattering amplitude

$$T = \rho(1 - i\rho\hat{K})^{-1}\hat{K} = e^{i\delta}\sin\delta. \tag{6}$$

The K-matrix is written as

$$\hat{K} = \frac{am}{2 + abq^2} + \frac{m_0\Gamma_0/\rho_0}{m_0^2 - m^2}, \tag{7}$$

where a is the scattering length, b the effective range and q the break-up momentum of the $K\pi$ system. We find $a = (2.52 \pm 0.22)\,(\mathrm{GeV}/c)^{-1}$, $b = (1.99 \pm 0.31)\,(\mathrm{GeV}/c)^{-1}$, $m_0 = (1338 \pm 8)$ MeV for the K-matrix pole and $\Gamma_0 = (403 \pm 22)$ MeV for the total width. The mass m_0 corresponds to the maximum of the scattering amplitude, where the phase δ passes through $\pi/2$. The corresponding resonance parameters (T-matrix poles) are $m_R = (1423 \pm 10)$ MeV and $\Gamma_R = (277 \pm 17)$ MeV, in close agreement with those of $K^*(1430)$ from ref. [25].

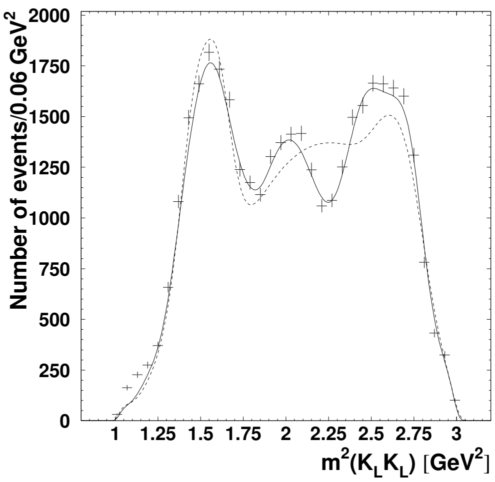

Fig. 2. Invariant mass squared distribution $m^2(K_L K_L)$ showing the data with error bars, the fit with one scalar resonance in $K_L K_L$ (dashed curve) and fit A with two scalars in $K_L K_L$ (full curve).

One phase of the complex coefficients $\alpha = a \exp i\phi$ is arbitrary and can be set to $\phi = 0$. Thus 17 parameters have to be determined by the fit: 6 coefficients a, 5 phases ϕ, 3 masses and 3 widths for K^{*0}, $f_2'(1525)$ and the $K\overline{K}$ S-wave around 1400 MeV. The fit converges to $\chi^2/N_{\mathrm{dof}} = 1255/(788-17) = 1.63$ and clearly fails to describe the $K\overline{K}$ mass spectrum (dashed line in fig. 2).

In a second attempt we introduce two scalar resonances in the $K\overline{K}$ amplitude. We assume that both have the same isospin and therefore use eqn. (3) for the K-matrix with two poles.

The χ^2 improves significantly to 1010/(788-21)=1.32 and the dip at 1500 MeV in the $K\overline{K}$ squared invariant mass spectrum is well described (full line in fig. 2). The corresponding resonance parameters (T-matrix poles) for the $K\overline{K}$ amplitude are:

$$(m, \Gamma) = (1404 \pm 10, 342 \pm 25)\ \mathrm{MeV},$$
$$(m, \Gamma) = (1517 \pm 12, 96 \pm 12)\ \mathrm{MeV}.$$

The errors include only statistical uncertainties from the fit to this hypothesis. The parameters for these resonances agree well with those for the

$f_0(1370)$ and $f_0(1500)$ [1–3,6]. We shall refer to this fit as fit A.

The resonance parameters for the K^* and for the $f_2'(1525)$ are compatible with the standard values [24]: The masses are 899 ± 2 MeV and 1526 ± 5 MeV, respectively, while the widths of 67 ± 3 MeV and 99 ± 11 MeV, are consistent with the standard widths broadened by an experimental resolution of $\sigma_r \approx 20$ MeV. The fit describes the $a_2 - f_2$ interference and contributions from both scalar and tensor resonances at $K\overline{K}$ masses around 1500 MeV without ambiguities.

We now consider the uncertainties of the parameters of the scalar resonances which arise from the influence of $f_0(980)/a_0(980)$ decaying into $K\overline{K}$. The $a_0(980)$ is parametrized by a 2×2 K-matrix with couplings to $K\overline{K}$ and $\pi\eta$. The parameters are taken from ref. [5]. The contribution is fixed to 10%, the average value from ref. [15]. The $f_0(980)$ is included as a third pole in the $I = 0$ $(K\overline{K})$ S-wave which couples to $K\overline{K}$ and $\pi\pi$. Fits with various combinations of parameters for $f_0(980)$ show that the two contributions from $a_0(980)$ and $f_0(980)$ cancel at low $K\overline{K}$ masses due to destructive interference. The $a_0(980)$ and $f_0(980)$ have only little effect on the parameters of $f_0(1500)$. We note that the χ^2 does not improve significantly and that the parameters of all partial waves beside the $(K\overline{K})$ S-wave do not change within errors.

The isovector $a_0(1450)$, observed in $\overline{p}p$ annihilation into $\pi^0\pi^0\eta$ and decaying into $\pi^0\eta$ [5], is also expected to decay into K_LK_L. We now study the correlation between $f_0(1370)$, $f_0(1500)$ and $a_0(1450)$. A fit with a free $a_0(1450)$ contribution does not converge since the parameters determining the $(K\overline{K})_S$ wave are highly correlated. Hence, we introduce a fixed $a_0(1450)$ contribution as an additional Breit-Wigner amplitude with fixed mass of 1470 and width of 265 MeV [5]. If we assume SU(3) [8] and a pseudoscalar mixing angle of $-17.3°$ [29], the branching ratio for $\overline{p}p \to a_0^0(1450)\pi^0 \to K_LK_L\pi^0$ can be calculated from the branching ratio for $\overline{p}p \to a_0^0(1450)\pi^0 \to \eta\pi^0\pi^0$ which is $(3.35 \pm 0.90) \times 10^{-4}$ [5]. We expect a contribution $a(a_0(1450))^2$ of $(7.7 \pm 2.1)\%$ to $\pi^0 K_L K_L$ from $a_0(1450) \to K_LK_L$.

The $\pi^0 K_L K_L$ Dalitz plot is now fitted with fixed $a_0(1450)$ contributions of 5% (fit A1), 10% (fit A2) and 15% (fit A3). The essential result is that the χ^2 remains stable compared to fit A (no $a_0(1450)$), showing that the $(K\overline{K})_S$ wave can be equally well described with two or three scalar resonances. We find that the total intensity of the $(K\overline{K})_S$ wave is stable and independent of the individual contributions: $a(K\overline{K})^2_S = |\alpha((K\overline{K})^{I=0}_S) + \alpha((K\overline{K})^{I=1}_S)|^2 = (71 \pm 3)\%$. The parameters of all other partial waves again are stable within errors.

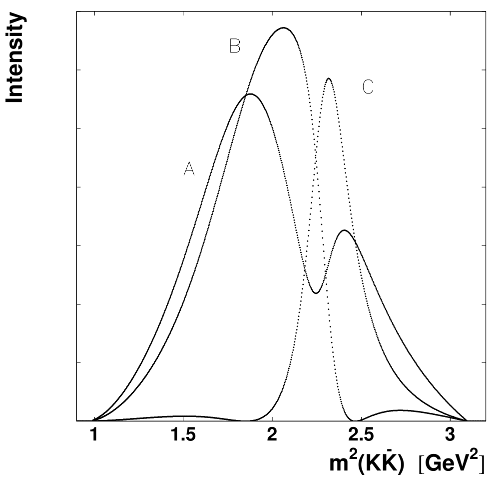

Fig. 3. Invariant mass squared distribution $m^2(K_LK_L)$ from fit A (with no $a_0(1450)$ contribution) showing the $(K\overline{K})_S$ wave (curve A) and the individual contributions from $f_0(1370)$ (curve B) and $f_0(1500)$ (curve C).

With increasing $a_0(1450)$ contribution, the amplitude $a(K\overline{K})^{I=0}_S$, which includes both $f_0(1370)$ and $f_0(1500)$, decreases due to constructive interference between the two isospin states. The $a_0(1450)$ intensity has a small influence on the T-matrix poles of the $I = 0$ $(K\overline{K})_S$ wave. The $f_0(1370)$ mass moves slightly downwards (from 1404 MeV for fit A to 1365 MeV for fit A3) while the width increases with increasing $a_0(1450)$ contribution (from 342 to 362 MeV). The mass and width of $f_0(1500)$ remain stable. For 7.7% $a_0(1450)$ contribution we find:

$$f_0(1370) : (m, \Gamma) = (1380 \pm 40, 360 \pm 50) \text{ MeV},$$
$$f_0(1500) : (m, \Gamma) = (1515 \pm 20, 105 \pm 15) \text{ MeV}.$$

The errors include both statistical and systematical errors. The latter are estimated from the variations with $a_0(1450)$ contribution and the influence of $a_0(980)$ and $f_0(980)$.

The $f_0(1370)$ and $f_0(1500)$ amplitudes overlap, leading to strong interference effects. This is illustrated in fig. 3 for fit A. The fractional contributions r_i are obtained by integrating the individual amplitudes over the Dalitz plot and normalizing to the total $(K\overline{K})_S$ wave. The contributions to $\pi^0 K_L K_L$ are then given by $a_i^2 = r_i \times a(K\overline{K})_S^2$ where $i = 1, 2$ for $f_0(1370)$ and $f_0(1500)$, respectively.

Using the branching ratio for $\overline{p}p \to \pi^0 K_S K_S$ of $(7.5 \pm 0.3) \times 10^{-4}$ [26,27] we obtain the branching ratio for $\overline{p}p \to \pi^0 f_0(1500) \to \pi^0 K\overline{K}$ given in the left column of table 1 as a function of $a_0(1450)$ contribution.

We now derive the branching ratios from fit A for the various intermediate states (table 2) and compare with existing data. The branching ratio for K^*K and the branching ratio for $a_2(1320)$ are in good agreement with those of ref. [15]. The branching ratio for $f_2(1270)$ agrees with the result in the reactions $\overline{p}p \to f_2(\to \pi^0\pi^0)\pi^0$ and $\overline{p}p \to f_2(\to \pi^+\pi^-)\pi^0$ from the $^1S_0$ initial state [6,28].

The $f_2'(1525)$ is observed for the first time in $\overline{p}p$ annihilation at rest. Assuming the OZI rule and no strange quark in the nucleon, the ratio of $f_2'(1525)$ to $f_2(1270)$ production rates is related to the mixing angle of the tensor nonet. A similar argument was used to derive the mixing angle of the pseudoscalar nonet [29]. We have, apart from phase space factors:

$$\frac{B(\overline{p}p \to f_2'\pi^0)}{B(\overline{p}p \to f_2\pi^0)} = \tan^2(\theta_{2++} - 35.3^\circ), \qquad (8)$$

where 35.3° is the ideal mixing angle. Our branching ratios (table 2) corrected by phase space factors and the Vandermeulen form factor [29] leads to $\theta_{2++} = (25.3 \pm 1.1)^\circ$, which agrees perfectly with 26° from the linear mass formula [24]. This result can be taken as a further consistency check of our analysis.

We now discuss our results on the $f_0(1500)$. The invariant coupling to $K\overline{K}$ is proportional to the branching ratio (table 1) divided by phase space. For the phase space we use the breakup momentum q and include a Godfrey-Isgur form factor $\exp(-q[GeV/c]^2/8\beta^2)$ with the cut-off parameter $\beta = 0.5$ [8]. The invariant coupling to $\pi\pi$ is derived similarly using our $\pi^0\pi^0$ data with $B(\overline{p}p \to f_0(1500)\pi^0, f_0(1500) \to \pi^0\pi^0) = (8.1 \pm 2.8) \times 10^{-4}$ [1]. The ratio of $K\overline{K}$ to $\pi\pi$ couplings is given in the second column of table 1. SU(3) predicts this ratio to be infinitely large for pure $s\overline{s}$ and equal to 1/3 for pure $u\overline{u} + d\overline{d}$.

Fit (% a_0 contribution)	Branching ratio $\times 10^{-4}$	$K\overline{K}/\pi\pi$ coupling
A (0)	7.7 ± 1.6	0.37 ± 0.14
A1 (5)	5.4 ± 1.3	0.26 ± 0.11
A2 (10)	4.5 ± 0.9	0.22 ± 0.09
A3 (15)	3.9 ± 0.9	0.19 ± 0.08

Table 1
Branching ratio for $\overline{p}p \to \pi^0 f_0(1500) \to \pi^0 K\overline{K}$ (left column) and relative invariant coupling $K\overline{K}/\pi\pi$ (right column) as a function of $a_0(1450)$ contribution.

$B(\overline{p}p \to K^*(892)K)$	$(10.45 \pm 0.82) \times 10^{-4}$
$B(\overline{p}p \to K^*(1430)K)$	$(5.51 \pm 0.55) \times 10^{-4}$
$B(\overline{p}p \to \pi a_2(1320))$	$(1.55 \pm 0.31) \times 10^{-2}$
$B(\overline{p}p \to \pi^0 f_2(1270))$	$(3.70 \pm 0.66) \times 10^{-3}$
$B(\overline{p}p \to \pi^0 f_2'(1525))$	$(9.38 \pm 1.49) \times 10^{-5}$
$B(\overline{p}p \to \pi^0 (K\overline{K})_S)$	$(2.1 \pm 0.2) \times 10^{-3}$

Table 2
Branching ratios including all decay modes and all charge combinations of the intermediate resonances.

From table 1, this ratio depends on the $a_0(1450)$ admixture. The error also contains a systematic uncertainty of 20% due to contributions from $a_0(980)$ and $f_0(980)$. The coupling of $f_0(1500)$ to $K\overline{K}$ is suppressed compared to $\pi\pi$ for any reasonable $a_0(1450)$ contribution.

We therefore conclude that the $f_0(1500)$ cannot be dominantly $s\overline{s}$. The suppression of $f_0(1500)$ decay into $K\overline{K}$ has already been noticed from the absence of signal in this region in earlier bubble chamber experiments [9]. However, no amplitude analysis was then available due to limited statistics. As we have shown, strong interferences in the $(K\overline{K})_S$ wave distort the $(K\overline{K})_S$ mass spectrum (see fig. 2) so that reliable masses and branching ratios cannot be derived without an amplitude analysis of a high statistics data sample. More precise couplings to $K\overline{K}$ will be available once the $a_0(980)$ and $a_0(1450)$ contributions are disentangled e.g. by studying the channel $\overline{p}p \to K^0 K^{\pm}\pi^{\mp}$. This work is in progress.

For the $f_0(1370)$, we find a branching ratio $\overline{p}p \to \pi^0 f_0(1370) \to \pi^0 K\overline{K}$ between $(18.8 \pm 4.0) \times 10^{-4}$ and $(7.0 \pm 1.6) \times 10^{-4}$ if the $a_0(1450)$ contribution to $\pi^0 K_L K_L$ is varied from 0 to 15%. Relative couplings to $\pi\pi$ are not derived since the determination of the $f_0(1370)$ contribution to the $\pi\pi$ S-wave is difficult due to the overlap with $f_0(980)$ and a broad background amplitude around 1000 MeV [1].

In any case, $f_0(1500)$ is not the $s\overline{s}$ state of the scalar $q\overline{q}$ nonet as claimed by ref. [30]. In turn, the narrow width of $f_0(1500)$ is incompatible with it being a $u\overline{u} + d\overline{d}$ member of the scalar $q\overline{q}$ nonet. The model of ref. [8] assumes that $f_0(1370)$ is the mainly $u\overline{u} + d\overline{d}$ member of the scalar $q\overline{q}$ nonet while $f_0(1500)$ is not the $s\overline{s}$ state due to its lack of coupling to $K\overline{K}$. Hence, this state is interpreted in ref. [8] as the ground state scalar glueball with a small $q\overline{q}$ admixture.

To summarize, the analysis of $\overline{p}p \to \pi^0 K_L K_L$ reveals at least two scalar mesons ($J^{PC} = 0^{++}$) with masses and widths consistent with $f_0(1370)$ and $f_0(1500)$. The $f_0(1500)$ is observed for the first time in its $K\overline{K}$ decay mode. The $a_0(1450)$ can neither be confirmed nor excluded. The $K\overline{K}$ couplings vary somewhat with the contribution assigned to the $a_0(1450)$ but the $f_0(1500)$ is not dominantly $s\overline{s}$.

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