$K\bar{K}$ and $4\pi^{\circ}$ DECAYS OF THE $f_0(1500)$

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The scalar meson $f_0(1500)$ has been discovered by studying proton-antiproton annihilations with the Crystal Barrel detector at LEAR (CERN). The final states $\pi^0\pi^0\pi^0$,$\pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $\pi^0\eta\eta'$ have already provided information on the $\pi\pi$, $\eta\eta$ and $\eta\eta'$ couplings of the $f_0(1500)$. The observation of the $f_0(1500) \rightarrow K\bar{K}$ decay mode presented here is based on the analysis of about 37,000 proton-antiproton annihilations at rest into the final state $K^0_L K^0_L \pi^0$. The $K^0_L K^0_L \pi^0$ events have been selected from an 'all-neutral' data sample taken with a liquid hydrogen target. A partial wave analysis has been performed. The coupling found for the $f_0(1500)$ to $K\bar{K}$ is relevant for its interpretation. The $f_0(1500)$ decay into $4\pi^{\circ}$ studied recently by the Crystal Barrel Collaboration gives an important input to the discussion on the nature of this state. This decay mode of $f_0(1500)$ will be also presented.

1 Introduction

Recent results from the Crystal Barrel experiment [1], [2] on the $f_0(1370)$ and $a_0(1450)$ scalar mesons have led to the proposition of a new scalar meson nonet [3]. It has been suggested there that the $s\bar{s}$ member of the scalar nonet should have a mass around 1600 MeV. In that context, the $f_0(1500)$ appears as a supernumerary state. This state has been observed by the Crystal Barrel Collaboration in its $\pi^0\pi^0$ [4], $\eta\eta$ [1], and $\eta\eta'$ [5] decay modes, with consistent masses and widths, giving the average (m,Γ)=(1509 $\pm$ 10,116 $\pm$ 17 MeV/c^2). The coupled channel analysis of high statistics Crystal Barrel data on $\bar{p}p$ annihilations into all neutral states $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$ and $\pi^0\eta\eta$ gives (m,Γ)=(1500 $\pm$ 10, 154 $\pm$ 30 MeV/c^2) [6]. In the following, we present new results, obtained with the Crystal Barrel detector, on additional decay modes of $f_0(1500)$, such as $f_0(1500) \rightarrow K\bar{K}$ and $f_0(1500) \rightarrow 4\pi^0$. The branching ratio into $K\bar{K}$ shows that the $f_0(1500)$ is not a pure $s\bar{s}$ meson. The strong decay to 4π leads to a relatively small partial width of the $f_0(1500)$ into $\pi^0\pi^0$. This in turn indicates that this resonance is unlikely to be a pure $q\bar{q}$ ($u\bar{u}$ + $d\bar{d}$) state.

2 The Crystal Barrel Detector

The Crystal Barrel spectrometer is located at the Low Energy Antiproton Ring (LEAR) at CERN. It is a multipurpose detector optimised for the measurement of charged particles (pions, kaons) and photons at LEAR energies. It combines excellent calorimetry and tracking with almost full solid angle coverage. The data presented in this paper were obtained by stopping 200 MeV/c antiprotons in a liquid hydrogen cryogenic target placed at the centre of the detector. A matrix of four silicon counters just before the target defines and monitors the incident beam. The target is surrounded by a pair of cylindrical multiwire proportional chambers (MPWC's) and a cylindrical drift chamber (JDC) to detect charged particles. Photons are detected in a barrel-shaped calorimeter which surrounds the drift chamber. The whole assembly is located in a solenoid magnet providing a homogeneous field of 1.5 T parallel to the antiproton beam. Since the results presented here depend on the photon calorimeter, we briefly describe its main characteristics.

The calorimeter consists of 1380 CsI(Tl) crystals, 16 radiation lengths each, read out by photodiodes. It covers the polar angles between 12° and 168° with full coverage in azimuth. The acceptance for shower detection is 95% of 4π. The energy calibration of the crystals is provided by the $\pi^{\circ} \rightarrow 2\gamma$ decays by imposing the mass of the π°. The energy resolution is given by $\sigma_E/E = 2.5\%/\sqrt[4]{E_\gamma[GeV]}$. Both polar and azimuthal angular resolutions vary with the photon energy from 20 mrad for isolated showers to 35 mrad for two or more showers merged into a single cluster of crystals. A more detailed description of the detector, the trigger conditions and the reconstruction procedure is given elsewhere [7].

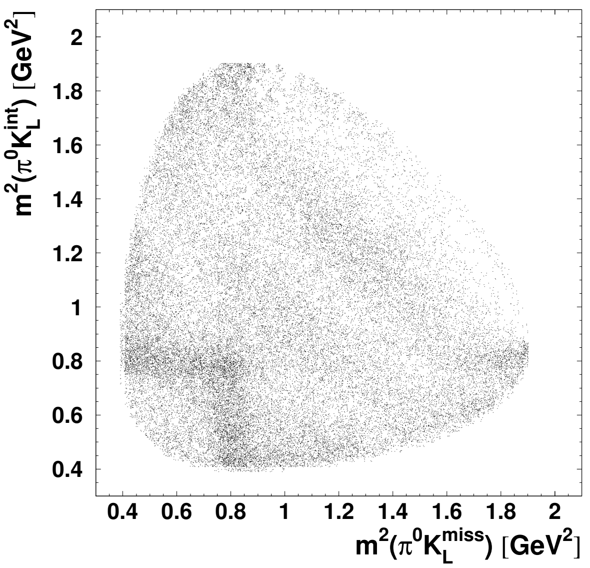

Figure 1: The $K_L K_L \pi^\circ$ Dalitz plot

3 $K_L K_L$ decay of the $f_0(1500)$

The analysis of the $f_0(1500) \rightarrow K_L K_L$ was based on 13.2×10^6 annihilations into neutral events which were collected by excluding, in the trigger, charged tracks. This data sample corresponds to $(3.38 \pm 0.26) \times 10^8$ $\bar{p}p$ annihilations. Annihilations into $K_L K_L \pi^\circ$ were selected by requiring three energy deposits in the calorimeter, two corresponding to photons from the π° decay, and one from an interacting K_L. The K_L interaction probability in CsI crystals has been measured to be (57.2 ± 2.7) % at 795 MeV/c [9]. The second K_L is non- interacting, but the measurement of the momentum of π° and the direction of the interacting K_L are sufficient to reconstruct the full event. The full kinematical reconstruction after the rejection of main channels contributing to the background ($\bar{p}p \rightarrow \omega K_L K_L$, where ω decays to $\pi^\circ\gamma$ and both K_L are missing; $\bar{p}p \rightarrow K_S K_L$, where the K_L and one γ from $K_S \rightarrow 2\pi^\circ \rightarrow 4\gamma$ are undetected), leaves a sample of 37,000 $K_L K_L \pi^\circ$ events. The background-subtracted and acceptance-corrected Dalitz plot is shown in Fig. 1. It exhibits clear evidence for $K^*(892)$. This is visible as two perpendicular bands in the lower left corner of the Dalitz plot. The presence of $(K_L K_L)$ resonances in the 1300-1500 MeV mass region is indicated by diagonal bands.

Assuming the dominance of annihilation from $\bar{p}p$ S-states in liquid hydrogen [8], only one $\bar{p}p$ initial state, namely $^1S_0$, contributes to $K_L K_L \pi^\circ$. The Dalitz plot has been analyzed by using the helicity formalism in terms of the isobar model in which the $\bar{p}p$ system is assumed to decay to the three-body final states via two-body intermediate states. The details of the analysis are given elsewhere [9]. Here, we recall only the most important results:

- The fit requires two scalar resonances in the $K_L K_L$ system. A clear evidence for that is shown in Fig. 2, where the invariant mass squared distribution of the $K_L K_L$ system is plotted. The peak at ~ 1500 MeV^2/c^4 is due to tensor resonances $f_2(1270)$ and $a_2(1320)$. The fit cannot describe the dip in the 1500 MeV region when only one scalar resonance is introduced in the K$\bar{\text{K}}$ amplitude. When two scalars are introduced in the K$\bar{\text{K}}$ S-wave, the K$\bar{\text{K}}$ mass spectrum around 1500 MeV is very well described. The masses and widths for these two scalar resonances agree reasonably well with those for $f_0(1370)$ and $f_0(1500)$ [6].
- The isovector meson $a_0(1450)$, originally observed by the Crystal Barrel Collaboration in its $\pi^\circ\eta$ decay mode in the annihilation into $\pi^0\pi^0\eta$ [2], is expected to decay into $K_L K_L$ as well. Therefore it can contribute to the final state $K_L K_L \pi^\circ$. Assuming a contribution from $a_0(1450)$ of 7 %, predicted by SU(3) for the isovector member of the 0^{++} $q\bar{q}$ nonet, the parameters of the scalar resonances are the following:

$f_0(1370)$:

$$(m, \Gamma) = (1380 \pm 40, 360 \pm 50\text{MeV}/c^2), \quad (1)$$

$f_0(1500)$:

$$(m, \Gamma) = (1515 \pm 20, 105 \pm 15\text{MeV}/c^2). \quad (2)$$

The $f_0(1500)$ invariant coupling γ^2 to K$\bar{\text{K}}$ is proportional to the branching ratio divided by the phase space. For the phase space we use the breakup momentum and include a Godfrey-Isgur formfactor [3]. The ratio $\gamma^2(f_0(1500) \rightarrow \text{K}\bar{\text{K}})/\gamma^2(f_0(1500) \rightarrow \pi\pi)$ is equal to (0.24 ± 0.10) for an $a_0(1450)$ contribution of 7.7 %. It varies from

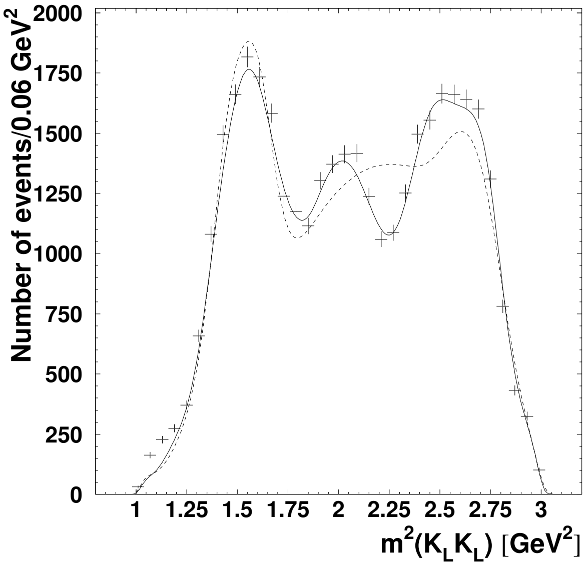

Figure 2: Invariant mass squared distribution $m^2(K_LK_L)$ showing the data with error bars. The dashed curve represents the fit with one scalar resonance in K_LK_L, whereas the full one shows the fit with two scalars in K_LK_L.

(0.37 ± 0.14) to (0.19 ± 0.08) with $a_0(1450)$ contributions from 0 to 15 %. SU(3) predicts for this ratio to be 1/3 for a pure $u\bar{u} + d\bar{d}$ state and infinite for a pure $s\bar{s}$ state. From the observed suppression of K$\bar{\text{K}}$ relative to $\pi\pi$ we conclude that $f_0(1500)$ is not a dominantly $s\bar{s}$ state.

4 Overall consistency of the results on $K_LK_L\pi^\circ$

In this section we present branching ratios and the mixing angle of the tensor meson nonet which arise as a by-product of the analysis of the reaction $\bar{p}p \to K_LK_L\pi^\circ$ and can be regarded as a consistency check of the analysis.

4.1 Branching ratios

Using the $K_LK_L\pi^\circ$ fit results we have calculated branching ratios for some intermediate states and compared them with existing data [see Tab. 1]. The good agreement gives confidence in the correctness of our fit results.

4.2 Mixing angle of the tensor nonet $\theta_{2^{++}}$

By applying the same technique as in ref. [13] for calculating the pseudoscalar mixing angle

Table 1: Branching ratios for $\bar{p}p$ annihilations from different initial states, compared to other experimental results.

Channel $\bar{p}p(^1S_0, I =)$	BR $\times 10^{-4}$ This work	BR $\times 10^{-4}$ Previous
$0 \to K^\star(892)K$	10.45 ± 0.82	8.4 ± 1.4 [10]
$1 \to K^\star(892)K$	1.17 ± 0.45	2.0 ± 0.4 [11]
$0 \to a_2(1320)\pi$	155 ± 31	133 ± 43 [10]
$1 \to f_2(1270)\pi^\circ$	37 ± 7	39 ± 11 [12]

(θ_{PS}=$-(17.3 \pm 1.8)^\circ$) one can obtain the mixing angle of the tensor nonet $\theta_{2^{++}}$. From the ratio of branching ratios BR($\bar{p}p \to f_2'(1525)\pi^\circ$)/ BR($\bar{p}p \to f_2(1270)\pi^\circ$) corrected by phase space factors and the Vandermeulen form factor we find $\theta_{2^{++}}$=$(25.3 \pm 1.1)^\circ$. To obtain this result we assumed the OZI rule and no strange quark content in the nucleon. This value of $\theta_{2^{++}}$ is in very good agreement with 26° from the linear mass formula. It should be noted that the total production rate $\bar{p}p(^1S_0) \to f_2'(1525)\pi^\circ$= $(9.38 \pm 1.49) \times 10^{-5}$ was measured here for the first time, since the f_2' has not been observed so far in $\bar{p}p$ annihilations at rest.

5 $4\pi^\circ$ decay of the $f_0(1500)$

The $f_0(1500)$ decay into $4\pi^\circ$ has been studied in $\bar{p}p \to 5\pi^\circ$ at rest. The Crystal Barrel detector is well suited to study $5\pi^\circ$ channel because of its excellent γ detection. The analysis was based on events selected from a zero-prong trigger data. The final sample contains the 25,000 $5\pi^\circ$ events which survive the kinematic fits to the $\bar{p}p \to 10\gamma$ final state (4C fit), and in a second step to the $\bar{p}p \to 5\pi^\circ$ final state (9C fit). The mass spectra for $2\pi^\circ$, $3\pi^\circ$ and $4\pi^\circ$ combinations, angular distributions and fits applying different intermediate resonances are discussed in detail in ref. [14]. Here we present only the results which pertain to the interpretation of the nature of the $f_0(1500)$ scalar state.

First of all the fits agree about the definite presence of the $f_0(1500)$, observed in its $4\pi^\circ$ decay mode. Its mass and width are compatible with earlier measurements. It was found that the $f_0(1500)$ decays with similar intensities into $\pi\pi(1330)$ and into $\sigma\sigma$, where σ stands for the full $\pi\pi$ S-wave amplitude. The product branching ratio for $f_0(1500)$ production with a decay into all 4π charge states not proceeding via $\rho\rho$ is determined to be $(0.81 \pm 0.12) \times 10^{-2}$. The corresponding BR($f_0(1500) \to 2\pi$)=$(0.24 \pm 0.04) \times 10^{-2}$ can be extracted from our $3\pi^\circ$ data [6]. One can now calculate the following ratio of branching ratios

$$r = \frac{\mathrm{BR}(f_0(1500) \to 4\pi)}{\mathrm{BR}(f_0(1500) \to \pi\pi)} = 3.4 \pm 0.8 \qquad (3)$$

This value of r leads to a ratio of invariant couplings which indicates that the transition $f_0(1500) \to 2\pi$ is much smaller than expected for a $q\bar{q}$ scalar decay of the type $0^{++} \to 0^{-+} + 0^{-+}$ (when compared, for instance, to $K_0^\star(1450) \to K\pi$). Therefore we conclude that $f_0(1500)$ is not a pure $q\bar{q}$ state.

6 Conclusions

In this section we present, briefly, an experimental status of the 0^{++}, I=0 states as seen in the Crystal Barrel data. We found that the $\pi\pi$-S-wave has four poles, namely, $f_0(980)$, $f_0(400-1200)$, $f_0(1370)$ and $f_0(1500)$. This pole structure is the result of the analysis of $\bar{p}p \to 3\pi^\circ$ data [4] and was later confirmed in a coupled channel analysis of three final states: $\bar{p}p \to 3\pi^\circ$, $\bar{p}p \to 2\pi^\circ\eta$ and $\bar{p}p \to \pi^\circ 2\eta$ [6]. Now we comment on these scalar states.

$f_0(980)$: This state is very well established, but neither its very small partial width to $\gamma\gamma$ ($\Gamma_{\gamma\gamma} = 0.56 \pm 0.11$) keV [15], nor its relative coupling to $K\bar{K}$ and $\pi\pi$ can give a definite answer on the nature of $f_0(980)$. Is it $q\bar{q}$ state, $2q2\bar{q}$ state or $K\bar{K}$ molecule?

$f_0(400-1200)$: This very broad elastic resonance can be interpreted as a $\pi\pi$ S-wave background for the $f_0(980)$. It probably contains broad $\pi\pi$ S-wave resonances assigned by the Particle Data Group to an elastic $f_0(1300)$ state [16].

$f_0(1370)$: It is observed in four channels, namely, $\pi^\circ\pi^\circ$, $\eta\eta$, 4π and $K\bar{K}$. The 4π decay mode is the dominant one.

$f_0(1500)$: It has been observed by the Crystal Barrel Collaboration in its decays to $\pi\pi$, $\eta\eta$, $\eta\eta'$, $K\bar{K}$ and 4π. The invariant couplings relative to $\pi\pi$ ($\pi\pi$ and $K\bar{K}$ include the charged modes) are the following:

$$\pi\pi \ : \eta\eta \ : \eta\eta' \ : K\bar{K} \ : 4\pi \ = \qquad (4)$$
$$3 : 0.70 \pm 0.27 : 1.00 \pm 0.46 : 0.57 \pm 0.24 : 11 \pm 3$$

The suppression of the $K\bar{K}$ decay for $f_0(1500)$ implies that it is not mainly the $s\bar{s}$ isoscalar state of the scalar nonet. The width of $f_0(1500)$ is too small for its interpretation as a $u\bar{u} + d\bar{d}$ member of the SU(3) nonet [3]. Moreover the three times bigger partial width of $f_0(1500)$ into 4π when compared to that into $\pi\pi$ suggests a non-$q\bar{q}$ nature for this state. Therefore the $f_0(1500)$ stands outside the scalar meson nonet as a supernumerary state. The interpretation of the nature of this scalar state has been discussed recently by C.Amsler and F.Close [3]. They suggested that the $f_0(1500)$ is predominantly a glueball mixed with $(u\bar{u} + d\bar{d})$ quarkonia.

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