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Results of the coupled channel analysis of $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ and $K^\pm K^0_S\pi^\mp$ final states from $\bar{p}p$ annihilation at rest in hydrogen targets at different densities

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Abstract

The $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ and $K^\pm K^0\pi^\mp$ final states produced by $\bar{p}p$ annihilation at rest at three different hydrogen target densities have been analyzed in the frame of a coupled channel analysis together with $\pi\pi$ and πK scattering data. Here we present the main results which concern masses, widths, $\pi\pi$ and $K\overline{K}$ partial widths of all the involved resonances ($J^P = 0^+, 1^-, 2^+$), the direct determination of $\Gamma_{K\overline{K}}/\Gamma_{\pi\pi}$ ratio for $f_0(1370)$ and $f_0(1500)$ ($\Gamma_{K\overline{K}}/\Gamma_{\pi\pi} = 0.91 \pm 0.20$ and $\Gamma_{K\overline{K}}/\Gamma_{\pi\pi} = 0.25 \pm 0.03$, respectively), the determination of $a_0(1300)$ parameters ($M = 1303 \pm 16$ MeV; $\Gamma = 92 \pm 16$ MeV) and the observation of two different high mass ρ signals associated to $\rho(1450)$ and $\rho(1700)$ ($M = 1182 \pm 30$ MeV; $\Gamma = 389 \pm 20$ MeV and $M = 1594 \pm 20$ MeV; $\Gamma = 259 \pm 20$ MeV, respectively).

1. Introduction

Here we present the main results of the first coupled channel analysis of the annihilation reactions at rest $\bar{p}p \to \pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ and $K^\pm K^0_S\pi^\mp$, measured, by the Obelix experiment, at three different densities of the hydrogen target (see [1] for the details). An articulated approach was developed in order to face up the problem of S- and P-wave contributions in $\bar{p}p$ annihilation at rest and to disentangle the complicated $K\overline{K}\pi$ dynamics.

As far as the first point is concerned, many experiments took the short cut of analysing $\bar{p}p$ annihilation at rest by assuming a pure S-wave contribution in liquid hydrogen. Nevertheless, as shown by the atomic cascade models [3] and the two-meson branching ratios analyses [4,5] a P-wave contribution of the order of 10% is expected so that this assumption turns out to be unacceptable for high statistics data samples. On the other side, the insertion of P-wave is unlikely due to the fact that its contribution in liquid hydrogen does not allow a reliable investigation of the complex P-wave annihilation dynamics. These considerations led us to collect $\bar{p}p$ annihilation data at different densities. In fact, the well-known mechanisms which regulate the formation and the deexcitation of the $\bar{p}p$ atom in the hydrogen medium [2] can be exploited to modulate the relative weights of the different partial waves contributing to annihilation at rest in three pseudoscalar meson final states, i.e., $^1S_0$, $^3S_1$, $^1P_1$, $^3P_1$ and $^3P_2$ ($^3P_0$ is forbidden by selection rules). For this reason each final state was collected in liquid hydrogen (LH), dominated by S-wave annihilation, low density hydrogen (corresponding to a pressure of 5 mbar, LP), dominated by P-wave annihilation, and hydrogen at standard conditions of density and pressure (NP), where comparable contributions from S- and P-wave annihilation are expected. As explained further on, the inspection of the experimental data gives a direct insight of the advantages of this technique, which represents a decisive progress to get a detailed understanding of final state dynamics in S and P partial waves of $\bar{p}p$ system.

Unlike $\pi\pi\pi$, the $K\overline{K}\pi$ final state is produced by intermediate resonant states of defined ($G = \pm 1$) and undefined G-parity so that both of the isospin components ($I = 0, 1$) of $\bar{p}p$ sources contribute (remarkable is the case of $K^*(892)$ produced by two interfering $\bar{p}p$ sources from five different partial waves). These circumstances make the investigation of $K^+K^-\pi^0$ dynamics a hard task and led us to introduce a different charge combination of the same final state, i.e., $K^\pm K^0\pi^\mp$. No additional parameters are required to describe its dynamics, $K^*(892)$ are produced in a completely different interference pattern and, above all, only $I = 1$ $K\overline{K}$ resonances can be produced. This fact turns out to be crucial in extracting the $I = 0$ component of $K\overline{K}$ dynamics from the $K^+K^-\pi^0$ final state.

Additional experimental information is provided by including in our data sets the $J^{PC} = 0^{++}$, $I^G = 0^+$, $\pi\pi \to \pi\pi$, $\pi\pi \to K\overline{K}$, and the $J^P = 0^+$, $I = 1/2$, $K\pi \to K\pi$ scattering data [6].

2. Experimental data and fit results

The annihilation reactions $\bar{p}p \to \pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ and $K^\pm K^0_S\pi^\mp$ at three different densities

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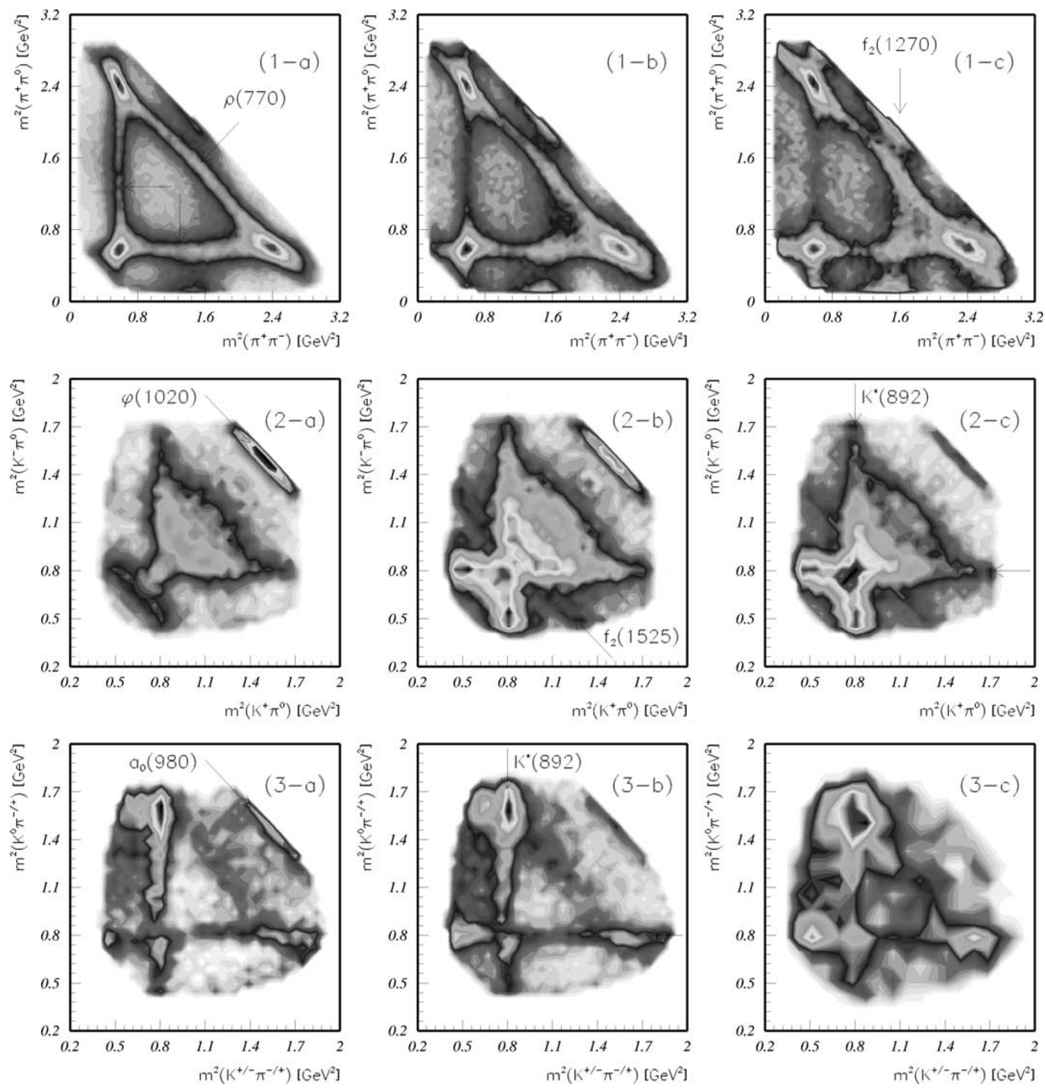

Fig. 1. Dalitz-plots (background subtracted) of the annihilation reactions $\bar{p}p \to \pi^+\pi^-\pi^0$ (first row), $\bar{p}p \to K^+K^-\pi^0$ (second row) and $\bar{p}p \to K^\pm K^0_S\pi^\mp$ (third row) in LH (a), NP (b) and LP (c) hydrogen targets. Statistics (in unit of 10^3 events): $\pi^+\pi^-\pi^0$, 808 (LH), 420 (NP), 260 (LP); $K^+K^-\pi^0$, 20 (LH), 23 (NP), 25 (LP); $K^\pm K^0_S\pi^\mp$, 10.6 (LH), 27 (NP), 3 (LP). XY axis: $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$ and $\pi^+\pi^0$ (bin size 0.032×0.032 GeV^2); $K^+K^-\pi^0$, $K^+\pi^0$ and $K^-\pi^0$ (bin size 0.045×0.045 GeV^2); $K^\pm K^0_S\pi^\mp$, $K^\pm\pi^\mp$ and $K^0\pi^\mp$ (bin size 0.045×0.045 GeV^2 in LH and NP, bin size 0.090×0.090 GeV^2 in LP).

(LH, NP, LP) were studied on data collected by the Obelix experiment at the Low Energy Antiproton Ring (LEAR) at CERN. The detailed description of the experimental apparatus, the triggers, the off-line selection, the background subtraction and the treatment of the apparatus efficiency can be found in Refs. [7,13]. Here we present the background subtracted Dalitz-plots of the reactions analyzed (Fig. 1).

The dominant contributions of $\rho(770)$ (observed in three charged states) and $f_2(1270)$ in $\pi^+\pi^-\pi^0$ channel and $K^*(892)$ (observed in two charged states) in $K^+K^-\pi^0$ and $K^\pm K^0_S\pi^\mp$ final states are clearly displayed by the experimental data. By looking at the figures from left to right, i.e., decreasing the density of hydrogen target, the fading of $\rho^0(770)$ and the enhancement of $f_2(1270)$ point out their dominant production respectively from S- and P-waves of the $\bar{p}p$ system (Fig. 1(1-a,b,c)). In the same way, a dominant S-wave production is clearly observed also in the case of $\phi(1020)$ (Fig. 1(2-a,b,c)) and $a_0(980)$ (Fig. 1(3-a,b,c)), while P-wave controls the $f_2'(1525)$ production (Fig.1(2-a,b,c)). The strong concentration of events in the central region between the $K^*(892)$ bands in the $K^+K^-\pi^0$, which is absent in the $K^\pm K^0_S\pi^\mp$ final state, is due to isoscalar resonances.

All the atomic physics involved in our problem is parametrized by the percentages $W^k(\rho_t)$ of the corresponding hyperfine levels (k labels ${}^1S_0$, ${}^3S_1$, ${}^1P_1$, ${}^3P_1$ and ${}^3P_2$, ${}^3P_0$ being forbidden by selection rules in three pseudoscalar meson final states). If $N_j(\rho_t)$ represents the number of selected events in each experimental Dalitz-plot (j labels the final state) the expected number of events in the bin $p'q'$ can be written as

$$D^{\rm Th}_{p'q'j}(\rho_t) = \sum_{k=1}^{N_{\rm pw}} \sum_{pq} N_j W^k \left|\hat{\beta}^k\right|^2 \epsilon_{p'q',pq} \left|\mathcal{F}^k_{pqj}\right|^2, \quad (1)$$

where $N_{\rm pw}$ is the number of partial waves, $\hat{\beta}^k$ the absolute normalization of the production parameters, $\epsilon_{p'q',pq}$ represents the apparatus efficiency and $\mathcal{F}^k_{pqj}$ the production amplitudes which describe the annihilation process (its detailed expression is given in Ref. [1]). In the frame of K-matrix and P-vector formalism these amplitudes are described by introducing series of poles of mass m_α coupled to $\bar{p}p$ system by the production parameters β^k_α and decaying into mesonic couples by the decay constants $g_{\alpha j}$ from which we got also the scattering amplitudes $\mathcal{T}^k_{jk}$. The pole parameters, together with $f^k_j(\rho_t) = N_j(\rho_t)W^k(\rho_t)|\hat{\beta}^k|^2$ are adapted to minimize the χ^2

Table 1
T-matrix parameters of the poles corresponding to the best fit solution (MeV units)

Res.	T-matrix parameters			
	M	Γ	Partial width	
$f_0(980)$	984 ± 15	29 ± 14	$\Gamma_{\pi\pi}$	21 ± 7
			$\Gamma_{K\bar{K}}$	5.4 ± 2
			$\Gamma_{\eta\eta}$	2.2 ± 1[a]
			$\Gamma_{4\pi}$	0.1 ± 0.04[a]
$f_0(400)$	1597 ± 30	726 ± 40	$\Gamma_{\pi\pi}$	602 ± 30
			$\Gamma_{K\bar{K}}$	120 ± 20
			$\Gamma_{\eta\eta}$	0.4 ± 0.2[a]
			$\Gamma_{4\pi}$	3.5 ± 1.0[a]
$f_0(1370)$	1373 ± 15	274 ± 20	$\Gamma_{\pi\pi}$	10.8 ± 2
			$\Gamma_{K\bar{K}}$	9.8 ± 2
			$\Gamma_{\eta\eta}$	107 ± 10[a]
			$\Gamma_{4\pi}$	146 ± 12[a]
$f_0(1500)$	1484 ± 10	125 ± 12	$\Gamma_{\pi\pi}$	35.8 ± 4
			$\Gamma_{K\bar{K}}$	9.0 ± 2
			$\Gamma_{\eta\eta}$	26.6 ± 4[a]
			$\Gamma_{4\pi}$	54 ± 8[a]
$K_0^*(1430)$	1436 ± 30	288 ± 35	$\Gamma_{\pi K}$	288 ± 35
$a_0(980)$	998 ± 10	72 ± 15	$\Gamma_{K\bar{K}}$	26 ± 6[b]
			$\Gamma_{\pi\eta}$	46 ± 8[a]
$a_0(1300)$	1303 ± 16	92 ± 16	$\Gamma_{K\bar{K}}$	91 ± 15
			$\Gamma_{\pi\eta}$	1 ± 0.5[a]
$\phi(1020)$	1019 ± 6	3.7 ± 0.5	$\Gamma_{K\bar{K}}$	3.7 ± 0.5

Res.	T-matrix parameters			
	M	Γ	Partial width	
$K_1^{*\pm}(892)$	895 ± 2	53 ± 4	$\Gamma_{\pi K}$	53 ± 1
$K_1^{*0}(892)$	899 ± 3	55 ± 4	$\Gamma_{\pi K}$	55 ± 2
$\rho^\pm(770)$	754 ± 5	132 ± 10	$\Gamma_{\pi\pi}$	132 ± 10
			$\Gamma_{K\bar{K}}$	0
			$\Gamma_{4\pi}$	< 0.02[a]
$\rho^0(770)$	752 ± 5	145 ± 10	$\Gamma_{\pi\pi}$	145 ± 10
			$\Gamma_{K\bar{K}}$	0
			$\Gamma_{4\pi}$	< 0.02[a]
$\rho(1450)$	1182 ± 30	389 ± 20	$\Gamma_{\pi\pi}$	187 ± 14
			$\Gamma_{K\bar{K}}$	< 3
			$\Gamma_{4\pi}$	209 ± 14[a]
$\rho(1700)$	1594 ± 20	259 ± 20	$\Gamma_{\pi\pi}$	18 ± 5
			$\Gamma_{K\bar{K}}$	55 ± 12
			$\Gamma_{4\pi}$	236 ± 14[a]
$f_2(1270)$	1251 ± 7	192 ± 10	$\Gamma_{\pi\pi}$	165 ± 9
			$\Gamma_{K\bar{K}}$	7.5 ± 2
			$\Gamma_{4\pi}$	19 ± 9[a]
$f_2'(1525)$	1521 ± 7	68 ± 7	$\Gamma_{\pi\pi}$	< 0.1
			$\Gamma_{K\bar{K}}$	68 ± 8
			$\Gamma_{4\pi}$	< 0.1[a]
$f_2(1565)$	1489 ± 15	204 ± 20	$\Gamma_{\pi\pi}$	204 ± 20
$a_2(1320)$	1319 ± 10	136 ± 25	$\Gamma_{K\bar{K}}$	–

Errors accounts for statistical and systematical deviations while values without errors are assumed fixed.

[a] Decay channels whose experimental data are not included in the analysis.

[b] Values not corrected for the real $K\bar{K}$ phase space.

function built with the theoretical amplitude, corrected for the overall efficiency, and the experimental data [1].

The best fit values of K-matrix masses and couplings can be found in [1], here we list only the physical state masses and widths (Table 1) calculated by the method explained in Ref. [8].

3. Discussion of the results

Concerning the atomic physics results the details can be found in Ref. [1]. Here we remark that the assumption of a pure S-wave annihilation in LH targets is meaningless due to the fact that P-wave contributions of about 15%, 25% and 30% are obtained in $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ and $K^\pm K^0_S\pi^\mp$ final states, respectively. On the other hand, if only LH data are available, due to the large number of parameters needed, the inclusion of P-waves is hopeless. Their contributions turn out to be too weak to be correctly determined although too strong to be neglected.

An important experimental check of the obtained partial wave deconvolution is represented by the density dependence of the partial wave percentages $W_k(\rho_t)$ (see Eq. (1)) that can be compared to the ones extracted by two meson annihilation branching-ratios. For instance in the case of $^1S_0$ and $^3S_1$ partial waves this dependence can be extracted from $\bar{p}p \to K^\pm K^0\pi^\mp\pi^+\pi^-$ spin-parity analysis [9] and from the branching ratio of $\bar{p}p \to K_S K_L$ [10], both performed at different hydrogen densities. The agreement is good [1].

Concerning the resonances the mains results are the following.

3.1. Vector mesons

The mass splitting of the $\rho(770)$ isospin multiplet determined by the fit has the following value

$$M_{\rho(770)^0} - M_{\rho(770)^\pm} = (-2 \pm 4)\ \text{MeV}. \tag{2}$$

The ratio of branching ratios

$$\frac{\text{BR}(p\bar{p} \to \rho^{\pm,0}\pi^{\mp,0}, {}^3S_1)}{\text{BR}(p\bar{p} \to \rho^{\pm}\pi^{\mp}, {}^1S_0)} = 25 \pm 5 \tag{3}$$

confirms the well-known S-wave dynamical selection rule, i.e., the $\rho\pi$ puzzle [11]. From P-waves such an evident effect is not observed nevertheless the enhanced production from $L = 2$ (L being the resonance-spectator angular momentum) is observed in $^1P_1$ partial wave (see also [13])

$$\frac{\text{BR}(p\bar{p} \to \rho^{\pm,0}\pi^{\mp,0}, {}^1P_1^{L=2})}{\text{BR}(p\bar{p} \to \rho^{\pm,0}\pi^{\mp,0}, {}^1P_1^{L=0})} = 8.1 \pm 2.0. \tag{4}$$

In this analysis $\rho(1450)$ is observed in $\pi\pi$ decay mode ($K\overline{K}$ being negligible) while the dominant 4π decay mode contributes to the overall inelasticity. The mass value confirms our previous determination [13] and remains remarkably lower than the PDG mean value [26]. In our opinion this fact fits in a problematic situation concerning $\rho(1450)$ parameters from many $p\bar{p}$ annihilation experiments (in $\pi\pi$ decay mode mass values below 1.3 GeV are found in 4π final state [12], while values of about 1.35–1.40 GeV are obtained in $\bar{p}d \to \pi^+\pi^-\pi^- p$ [14] and $\bar{n}p \to \pi^+\pi^+\pi^-$ [15]).

Our previous determinations of $\rho(1700)$ parameters [16] are confirmed [27].

The mass splitting of isospin doublet determined by the fit has the following value

$$M_{K^*(892)^0} - M_{K^*(892)^\pm} = (4 \pm 2)\ \text{MeV}. \tag{5}$$

We found that the production of $K^*(892)K$ is regulated by a dynamical selection rule which suppresses, in each partial wave, one of the two $\bar{p}p$ isospin sources. This effect, observed in S-wave [19], is now measured for the first time also in P-wave. In the case of $K^+K^-\pi^0$ final state [20] where the K^* interference pattern is isospin independent, we get

$$\frac{\text{BR}(p\bar{p} \to K^*K, I=1)}{\text{BR}(p\bar{p} \to K^*K, I=0)} = \begin{cases} 0.40 \pm 0.07 & {}^1S_0, \\ 5.8 \pm 0.9 & {}^3S_1, \\ 0.25 \pm 0.02 & {}^1P_1, \\ 0.10 \pm 0.01 & {}^3P_1, \\ 5.03 \pm 0.34 & {}^3P_2. \end{cases}$$

Besides the necessity to understand the origin of this dynamical selection rule, interesting phenomena can be addressed to these results. For instance, the huge OZI-rule violating $\phi\pi$ production from $^3S_1$ and its suppression from $^1P_1$, can be related, through the $K^*(892)K$ rescattering in the final state, to the enhancement of K^*K production from $I = 1$ and $I = 0$ $\bar{p}p$ sources in $^3S_1$ and $^1P_1$ partial wave respectively [17].

We confirm the strong $\phi(1020)\pi^0$ production from $^3S_1$ partial wave and the negligible contribution of $^1P_1$: BR$(p\bar{p} \to \phi\pi^0) = (5.0 \pm 1.8) \times 10^{-4}$ in LH, $(2.9 \pm 1.0) \times 10^{-4}$ at NP and $(1.2 \pm 0.4) \times 10^{-4}$ at LP, in agreement with the previous determination [18].

3.2. Tensor mesons

In the present analysis the $a_2(1320)$ is observed in K^+K^- and in $K^\pm K^0$ decay mode which represent about the 5% of the total. The following branching-ratios are obtained BR$(p\bar{p} \to a_2(1320)^+\pi^-;\ a_2^+ \to K^+\overline{K}^0)$: LH, $(3.88 \pm 0.90) \times 10^{-4}$; $^1S_0$ of LH, $(2.45 \pm 0.50) \times 10^{-4}$. Both values agree within the errors with the bubble chamber [19] and Crystal Barrel [21,33] measurements. From the analysis of $p\bar{p} \to \pi^+\pi^-\eta$ [23] we can calculate the BR$(p\bar{p} \to a_2(1320)^+\pi^-;\ a_2^+ \to \eta\pi^+)$: LH, $(37.2 \pm 3.4) \times 10^{-4}$; $^1S_0$ of LH, $(23.7 \pm 1.9) \times 10^{-4}$, which agree with [22]. In spite of the consistency among these experimental measurements, the $a_2(1320)$ decay ratio is $\Gamma_{K\overline{K}}/\Gamma_{\eta\pi} = 0.10 \pm 0.02$, which is about a factor 3 lower than the PDG one. From the analysis of $p\bar{p} \to \pi^+\pi^-\pi^+\pi^-$ [24] we can also calculate BR$(p\bar{p} \to a_2(1320)^+\pi^-;\ a_2^+ \to \rho^0\pi^+)$: LH, $(51.0 \pm 5.0) \times 10^{-4}$; $^1S_0$ of LH, $(37.1 \pm 4.0) \times 10^{-4}$. Correcting for the unobserved $\rho^+\pi^0$ decays we can determine the ratio $\Gamma_{K\overline{K}}/\Gamma_{\rho\pi} = 0.036 \pm 0.07$ by using LH or 0.032 ± 0.007 by using $^1S_0$ in LH, which is a factor of 2 lower than PDG. From this scenario it is not clear which decay channel is responsible for the discrepancy with PDG.

Concerning $f_2(1270)\pi^0$ we get the following ratios

$$\frac{\Gamma_{K\overline{K}}}{\Gamma_{\pi\pi}} = 0.045 \pm 0.010,$$

$$\frac{\text{BR}(p\bar{p} \to f_2\pi^0,\ f_2 \to K\overline{K})}{\text{BR}(p\bar{p} \to f_2\pi^0,\ f_2 \to \pi\pi)} = \begin{cases} 0.043 \pm 0.010 & ^1S_0, \\ 0.045 \pm 0.010 & ^3P_1, \\ 0.048 \pm 0.010 & ^3P_2 \end{cases}$$

in agreement with the PDG value [26].

Possible OZI-rule violation effects in $f_2'(1525)\pi^0$ production can be investigated by measuring the following ratio of production branching ratios [18,25]

$$\frac{\text{BR}(p\bar{p} \to f_2'(1525)\pi^0)}{\text{BR}(p\bar{p} \to f_2(1270)\pi^0)} = \begin{cases} 0.028 \pm 0.006 & ^1S_0, \\ 0.026 \pm 0.003 & ^3P_1, \\ 0.051 \pm 0.020 & ^3P_2 \end{cases}$$

the comparison with the OZI-rule theoretical expectation $R_{\text{th}} = \rho_{f_2'}/\rho_{f_2} \tan^2(\theta_{2^{++}} - \theta_{\text{id}}) = 0.022$ ($\theta_{2^{++}} = 28^\circ$ [26]) excludes strong OZI-rule violation effects from S and P waves.

A third pole, we associated to $f_2(1565)$ is required mainly by low density pion data. Due to the fact that the 4π decay mode was set to zero (no experimental indications are available on 4π decay mode) only the mass and the total width of the resonance can be measured by the present analysis (Table 1). Although this resonance is very close to $f_2'(1525)$, its larger width and the reduced $K\overline{K}$ coupling make the two signals distinguishable. Its dominant production from $^3P_2$ partial wave is observed and confirms our previous determination [13].

3.3. Scalar mesons

The analysis confirms the negligible contribution of P-wave in $a_0(980)$ production clearly observable by the direct inspection of the experimental data. By using the $a_0\pi$ production branching ratios in $K\overline{K}\pi$ (present analysis) and $\pi^+\pi^-\eta$ ($(8.2 \pm 0.5) \times 10^{-4}$ in LH) [23] we get the following ratio of partial widths: $\Gamma_{K\overline{K}}/\Gamma_{\eta\pi} = 0.23 \pm 0.04$ in agreement with the PDG [26]. A second a_0 pole of mass around 1300 MeV is required especially by $K^\pm K^0_S\pi^\mp$ data in the steep slope of $a_2(1320)$ signal confirming the previous Obelix analysis result ($M = 1290 \pm 10$ MeV [27]). Higher mass values [33] do not improve the χ^2, moreover if a mass value of 1450 MeV is fixed the resonance fraction becomes negligible.

Many of the properties of $f_0(980)$, as known, are related to the closeness to $K\overline{K}$ threshold. By studying the behavior of the real and imaginary part of the inverse propagator matrix we determine a total width of $\Gamma = 174 \pm 10$ MeV reduced, by the threshold effect, to the value listed in Table 1 [8].

The physical state associated to f_0(400–1200) looks like a very broad structure which departs completely from the Breit–Wigner shape. Also in this case, the physical pole parameters listed in Table 1 are obtained by calculating the imaginary part of the inverse propagator matrix at the mass value which zeroes its real part [8].

The $f_0(1370)$ turns out to be coupled mainly to the unobserved $\eta\eta$ and 4π channels. Concerning the observed decay channels we get

$$\frac{\Gamma_{K\overline{K}}}{\Gamma_{\pi\pi}} = 0.91 \pm 0.20,$$

$$\frac{\mathrm{BR}(p\bar{p} \to f_0\pi^0, f_0 \to K\overline{K})}{\mathrm{BR}(p\bar{p} \to f_0\pi^0, f_0 \to \pi\pi)} = \begin{cases} 1.00 \pm 0.20 & {}^1S_0, \\ 0.94 \pm 0.20 & {}^3P_1. \end{cases}$$

In the case of $f_0(1500)$, relevant are the $\pi\pi$ and $K\overline{K}$ decay modes, here measured for the first time in a coupled-channel analysis of annihilation data

$$\frac{\Gamma_{K\overline{K}}}{\Gamma_{\pi\pi}} = 0.25 \pm 0.03,$$

$$\frac{\mathrm{BR}(p\bar{p} \to f_0\pi^0, f_0 \to K\overline{K})}{\mathrm{BR}(p\bar{p} \to f_0\pi^0, f_0 \to \pi\pi)} = \begin{cases} 0.24 \pm 0.04 & {}^1S_0, \\ 0.30 \pm 0.04 & {}^3P_1 \end{cases}$$

the agreement with the recent determinations of Refs. [28,29] is satisfactory. If we accept the hypothesis of a $q\bar{q}$ nature of $f_0(1370)$ (we underline that the peculiar decay modes of this resonance, mainly the 4π decay mode, make this assumption questionable) a dominant $s\bar{s}$ higher mass meson is expected. In this case these measurements rule out the possibility that $f_0(1500)$ could be such an $s\bar{s}$ meson and lead to consider the possibility of relevant gluonic components [32].

4. Conclusions

The present analysis was designed to perform a coupled channel study of $\pi\pi$ and $K\overline{K}$ decay modes of light mesons. The complex $K\overline{K}$ dynamics is resolved by using two different charge combinations of $K\overline{K}\pi$ final state, i.e., $K^+K^-\pi^0$ accessible to $I = 0, 1$ resonances and $K^\pm K^0_S\pi^\mp$ were only $I = 1$ states can be produced. To avoid the systematic uncertainties arising from partial wave separation, we developed an approach, based on the use of hydrogen targets of three different densities, by which we obtain data samples with different mixtures of S- and P-wave hyperfine levels. The variation with the hydrogen density of their percentages can be checked by means of two meson branching-ratios giving an experimental basis to the principal source of systematics in this kind of analyses. Our results show clearly that, regardless of the target density, S- and P-waves play an essential role in annihilation at rest and have to be necessarily included in partial wave analysis. The obtained results concern partial wave fractions, masses, partial widths, total widths and fractions of vector, scalar and tensor mesons. Here we discuss only the main conclusions, related essentially to tensor and scalar mesons [1].

Besides the well-known $f_2(1270)$ and $f_2'(1525)$ a third $I = 0$ resonance, i.e., $f_2(1565)$, coupled only to the $\pi\pi$ channel is observed ($M = 1489 \pm 15$ MeV; $\Gamma = 204 \pm 20$ MeV). No significative OZI-rule violation effects have been found in $f_2(1270)\pi^0$–$f_2'(1525)\pi^0$ production.

Four different poles in scalar isoscalar ($f_0(400$–$1200)$, $f_0(980)$, $f_0(1370)$ and $f_0(1500)$), one in scalar isospinor ($K_0^*(1430)$) and two in scalar isovector sectors ($a_0(980)$, $a_0(1300)$) are necessary to reproduce the experimental data. Of the two higher mass scalar isoscalar poles, i.e., $f_0(1370)$ and $f_0(1500)$, the mass and the total width of the first are compatible with the values expected for a dominant $u\bar{u} + d\bar{d}$ state ($M = 1373 \pm 15$ MeV; $\Gamma = 274 \pm 20$ MeV), the mass scale of the nonet being fixed by $K_0^*(1430)$. For this reason if we interpret the $f_0(1500)$ as a pure $q\bar{q}$ state we are forced to require a dominant $s\bar{s}$ component. Nevertheless, the obtained ratio of partial widths $\Gamma_{K\overline{K}}/\Gamma_{\pi\pi} = 0.25 \pm 0.03$ suggests a small $s\bar{s}$ contribution not compatible with the large value expected for a genuine $s\bar{s}$ state. This fact leads to reject the hyphotesis of a pure $q\bar{q}$ state in favour of a relevant gluonic component. The definitive assignment of spin $J = 0$ to $f_J(1700)$ [29] and the large fraction of $s\bar{s}$ in this state [30], the suppression of $f_0(1500)$ in $\gamma\gamma$ collisions and the observation of $f_0(1700)$ [31], support this interpretation (see also [32]). The remaining members of the $J^P = 0^+$ $SU(3)$ multiplet are the four states associated to $K_0^*(1430)$, here observed in interfering states of different charge, and the $a_0(1300)$ observed in all its charged states. The $a_0(1300)$ mass parameters ($M = 1303 \pm 16$ MeV; $\Gamma = 92 \pm 16$ MeV) confirm our previous measurement in single channel analysis [27] and agree with the values expected for a $u\bar{u} + d\bar{d}$ state which has to be lighter than $K_0^*(1430)$.

The completion of $J^P = 0^+$ $SU(3)$ multiplet prevents to interpret the remaining three scalars $f_0(980)$,

$f_0(400\text{–}1200)$ and $a_0(980)$, as $q\bar{q}$ states. These states could be associated to the mesonic molecules $(qq\bar{q}\bar{q})$ predicted by Jaffe [34]. These molecules, formed by the QCD Breit interaction, occur in the lowest energy state in a $3_f \otimes \bar{3}_f$ nonexotic flavour configuration with an inverted mass spectrum where the lower mass $I = 0$ molecular state ($f_0(400\text{–}1200)$) is followed by four intermediate mass $I = 1/2$ states (probably observed by [35], see also [36]) and by three $I = 1$ ($a_0(980)$) and one $I = 0$ ($f_0(980)$) mass degenerate states. The recent measurements of $f_0(980)$ and $a_0(980)$ radiative branching-ratios [37,38] support this interpretation. If the molecular states hyphotesis is correct also excited states in $6_f \otimes \bar{6}_f$ flavour configuration are expected in the energy region above 1 GeV [34]. These 36 states are shared among the isospin values $I = 2(0), 3/2(1), 1(0, 2), 1/2(1, 3), 0(0, 2, 4)$ (between brackets are indicated the number of strange quarks contained in the corresponding $qq\bar{q}\bar{q}$ state). The $I = 2$ resonance, observed in $\pi^+\pi^+$ invariant mass at about 1.4 GeV [39] fixes the mass value of a $qq\bar{q}\bar{q}$ state without strange quarks. This fact could suggest that also the $I = 1$ resonance $a_0(1450)$, observed in $\eta\pi$ channel by the Crystal Barrel Collaboration, could be a $qq\bar{q}\bar{q}$ state without strange quarks. Following this hyphotesis the quark line rule and the dominance of the rearrangement diagrams could also explain why this state is observed by Crystal Barrel in $\eta\pi$ and $\eta'\pi$ and not by Obelix in $K\overline{K}$. In this frame also an alternative interpretation of $f_0(1370)$ and $f_0(1500)$ is possible. In fact if we assume these states as $qq\bar{q}\bar{q}$ states or $qq\bar{q}\bar{q}\text{–}q\bar{q}$ mixed states the large 4π decay mode of $f_0(1370)$ and the relatively reduced $K\overline{K}$ coupling of $f_0(1500)$ could be explained by the quark line rule and the dominance of the rearrangement diagrams.

References

[1] A. Bertin, et al., Eur. Phys. J. C 26 (2003) 371.
[2] C.J. Batty, Rep. Prog. Phys. 52 (1989) 1165.
[3] G. Reifenrother, E. Klempt, Nucl. Phys. A 503 (1989) 885; E. Borie, M. Leon, Phys. Rev. A 21 (1980) 1460.
[4] C.J. Batty, Nucl. Phys. A 601 (1996) 425.
[5] G. Bendiscioli, et al., Nucl. Phys. A 686 (2001) 317.
[6] G. Grayer, et al., Nucl. Phys. B 75 (1974) 189; A. Etkin, et al., Phys. Rev. D 25 (1982) 1786; D. Aston, et al., Nucl. Phys. B 296 (1988) 493.
[7] A. Adamo, et al., Sov. J. Nucl. Phys. 55 (1992) 1732.
[8] M. Bargiotti, et al., Eur. Phys. J. A 2 (2002) 1.
[9] A. Bertin, et al., Phys. Lett. B 385 (1996) 493.
[10] A. Bertin, et al., Phys. Lett. B 386 (1996) 486.
[11] B. May, et al., Z. Phys. C 46 (1990) 191; B. May, et al., Z. Phys. C 46 (1990) 203.
[12] A. Bertin, et al., Phys. Lett. B 414 (1997) 220; A. Bertin, et al., in: Proc. Conf. Hadron Spectroscopy, BNL, August 24–31, 1997.
[13] A. Bertin, et al., Phys. Lett. B 408 (1997) 476.
[14] A. Abele, et al., Phys. Lett. B 450 (1999) 275.
[15] A. Bertin, et al., Phys. Rev. D 57 (1998) 55.
[16] A. Bertin, et al., Phys. Lett. B 434 (1998) 180.
[17] O. Gortchakov, M.P. Locher, V.E. Markushin, S. von Rotz, Z. Phys. A 353 (1996) 447.
[18] A. Alberico, et al., Phys. Lett. B 438 (1998) 430.
[19] B. Conforto, et al., Nucl. Phys. B 3 (1967) 469; A. Bettini, et al., Nuovo Cimento A 63 (1969) 1199.
[20] A. Abele, et al., Phys. Rev. D 57 (1998) 3860.
[21] S. von Dombrowski, PhD thesis, Zurich University, 1995; A. Abele, et al., Phys. Lett. B 385 (1996) 425.
[22] C. Amsler, et al., Phys. Lett. B 333 (1994) 277; C. Amsler, et al., Phys. Lett. B 355 (1995) 425.
[23] Obelix Collaboration, Nucl. Phys. A 655 (1999) 35c; Obelix Collaboration, in: T. Bressani, et al. (Eds.), WHS99, Proceedings of Workshop on Hadron Spectroscopy, Frascati, Italy, p. 37.
[24] A. Bertin, et al., Phys. Lett. B 414 (1997) 220; G. Bendiscioli, et al., in preparation.
[25] C. Amsler, et al., Eur. Phys. J. C 23 (2002) 29.
[26] Review of Particle Physics, Eur. Phys. J. C 15 (2000) 1.
[27] A. Bertin, et al., Phys. Lett. B 434 (1998) 180.
[28] C. Amsler, et al., Phys. Lett. B 355 (1995) 425; A. Abele, et al., Phys. Lett. B 385 (1996) 425.
[29] D. Barberis, et al., Phys. Lett. B 462 (1999) 462.
[30] F.E. Close, A. Kirk, et al., Phys. Lett. B 483 (2000) 345.
[31] M. Acciarri, et al., Phys. Lett. B 501 (2001) 173; R. Barate, et al., Phys. Lett. B 472 (2000) 189.
[32] C. Amsler, et al., Phys. Lett. B 541 (2002) 22.
[33] A. Abele, et al., Phys. Rev. D 57 (1998) 3860.
[34] R. Jaffe, Phys. Rev. D 15 (1977) 267; R. Jaffe, Phys. Rev. D 15 (1977) 281; R. Jaffe, hep-ph/0001123.
[35] E791 Collaboration, hep-ex/0212057.
[36] S. Cherry, M.R. Pennington, Frascati Spring School, Italy, May, 2000.
[37] A. Aloisio, et al., hep-ex/0107024.
[38] F.E. Close, A. Kirk, hep-ph/0106108.
[39] A. Filippi, et al., Phys. Lett. B 495 (2000) 284.