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4π-DECAYS OF SCALAR MESONS

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ABSTRACT

The preliminary analysis of four high statistic 5π data sets taken with the Crystal Barrel detector shows that at least two scalar states are needed to describe the data, the $f_0(1370)$ with $m = 1400 \pm 30\,\mathrm{MeV/c^2}$, $\Gamma = 251 \pm 45\,\mathrm{MeV/c^2}$ and the $f_0(1500)$ with mass and width compatible with previous findings. The first one decays into $\sigma\sigma$ and $\rho\rho$, the second one into $\sigma\sigma$ and $\pi^*(1300)\pi$. The $\pi^*(1300)$ is found to decay dominantly into $\rho\pi$ ($\sigma\pi < 10\%$), as expected for a radial excitation of the π. The 4π decays of both scalar states are very important, for the $f_0(1370)$ it indeed dominantes all other decay modes observed so far.

1 Intrduction

The $f_0(1370)$ and $f_0(1500)$ have been studied in detail in $\bar{p}p$ annihilations at rest by the Crystal Barrel Collaboration [1)– 6)] The peculiar decay pattern of the $f_0(1500)$ into two pseudo-scalar mesons led to the speculation it may be the scalar glueball mixed with normal scalar mesons [7) 8)]. Of particular importance for any interpretation are the decays of the $f_0(1500)$ into four pions [9)]. The existence of the $f_0(1370)$ which is crucial for the interpretation of the scalar nonet and the glueball discussion has been clouded by a broad structure coupling to $\pi\pi$ and currently referred to as

$f_0(400-1200)$ [10]. Earlier publications on 3–pseudoscalar final states often led to ambiguities in the number of poles in the $\pi\pi$ system. Often, both a 3–pole solution excluding the $f_0(1370)$ and a 4–pole solution including it were found to describe the data.

2 Data and partial wave analysis

In order to address these questions, we have examined both $\bar{p}d$ and $\bar{p}p$ annihilation at rest into five–pion final states.

$$\bar{p}p \to 5\pi^0 \quad \bar{p}d \to \pi^- 4\pi^0 p_{spectator} \quad \bar{p}p \to \pi^+\pi^- 3\pi^0 \quad \bar{p}d \to \pi^+ 2\pi^- 2\pi^0 p_{spectator}$$

The different data sets were recorded by stopping antiprotons from LEAR in a liquid hydrogen or in a liquid deuterium target. The Crystal Barrel detector is equipped for charged particle tracking in a magnetic field of 1.5 T and is able to measure photons with high precision in a CsI calorimeter covering 98% of 4π [11]. The data was taken with a trigger on the corresponding number of charged particle with more than 30 000 events for all four reactions. In annihilations in deuterium we asked for a proton momentum lower than 100 MeV/c in order to select reactions on quasi-free neutrons. In addition an anticut on $\eta, \omega \to 3\pi$ was applied.
The study of $\bar{p}n$ annihilation offers distinctive advantages. The $\bar{p}n$ system has only isospin I=1, hence annihilation from S-wave into five pions is restricted to the $^1S_0$ state. (This is also the case for $\bar{p}p \to 5\pi^0$ due to C-parity.) Different data sets have a different sensitivity for different resonances and decay modes. Hence the use of all four data sets provides important constraints.
The neutral 4π invariant mass distributions for the four data sets are shown in Fig.1. In all data a clear enhancement compared to phase space is visible in the region of 1500 MeV/c^2. This is a first hint for the existence of the $f_0(1500)$. Fig.2 shows some additional invariant mass distributions, now only for the $\pi^+2\pi^-2\pi^0$ data. Fig.1 and 2 suggest contributions from particles like $f_0(1500)$, $\rho'(1450)$ and the charged and neutral $\rho(770)$. In addition, particles like the σ (σ is always used as shorthand for the full $\pi\pi$-S-wave) and the $\pi^*(1300)$ may contribute.

The amplitudes listed in Tab.1 are used in the fits. Note that Clebsch-Gordon coefficients may vanish for some amplitudes in some special final states. In the following the results are summarized obtained for the π^* and the scalar mesons.

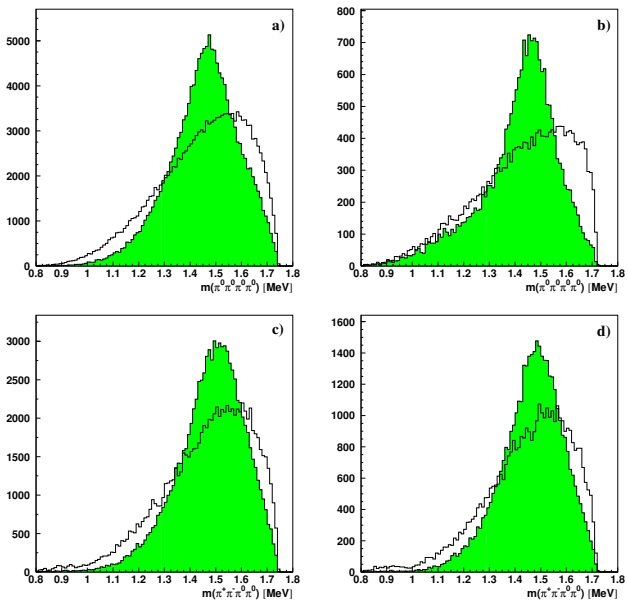

Figure 1: *Neutral 4π invariant mass for all four data sets: (a) $5\pi^0$, (b) $\pi^-4\pi^0$, (c) $\pi^+\pi^-3\pi^0$ and (d) $\pi^+2\pi^-2\pi^0$. The shaded distribution shows the data, the curve the phasespace plotted for the same number of events.*

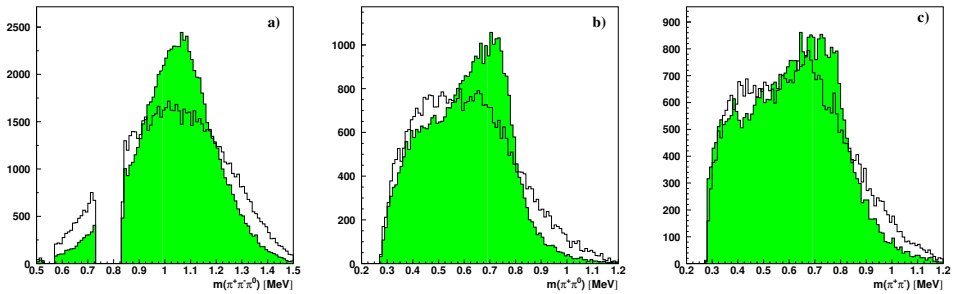

Figure 2: *(a) $\pi^+\pi^-\pi^0$, (b) $\pi^+\pi^0$, and (c) $\pi^+\pi^-$ (d) invariant mass of the $\pi^+2\pi^-2\pi^0$ data set. The shaded distribution shows the data, the curve the phasespace.*

2.1 The $\pi^*(1300)$

The $\pi^*(1300)$ plays a role in the $\pi^*\pi$-decays of f_0 and ρ'-states and in the direct production with a σ or a ρ. It was found that the π^* decays dominatly into $\rho\pi$. Fig.3a,b shows a scan of the π^* mass and width for the $\pi^-4\pi^0$-data set. While the scan for the $\pi^* \to \rho\pi$-decay shows a clear maximum in $\log(\mathcal{L})$, which indicates that we observe this decay mode, the scan for $\pi^* \to \sigma\pi$ does not show evidence for the $\sigma\pi$ decay mode. If both partial widths are left free we get an upper limit of 10% for

Table 1: *Amplitudes examined for the four 5π data sets. In the amplitudes given the π^*, a_1, h_1 and the a_2 are decaying in to $\rho\pi$. Amplitudes including the $\pi^* \to \sigma\pi$ decay have also been tried in the fit but were found to be negligible.*

	$5\pi^0$	$\pi^-4\pi^0$	$\pi^+\pi^-3\pi^0$	$\pi + 2\pi^-2\pi^0$	
$\bar{p}N \to f_0\pi$; $f_0 \to \sigma\sigma$	x	x	x	x	$f_0(1370)$,
$\bar{p}N \to f_0\pi$; $f_0 \to \rho\rho$			x	x	$f_0(1500)$
$\bar{p}N \to f_0\pi$; $f_0 \to \pi^*\pi$	x	x	x	x	
$\bar{p}N \to f_0\pi$; $f_0 \to \pi^*\pi$			x	x	
$\bar{p}N \to f_0\pi$; $f_0 \to a_1\pi$			x	x	
$\bar{p}N \to \rho'\pi$; $\rho' \to \rho\sigma$		x	x	x	$\rho'(1450)$,
$\bar{p}N \to \rho'\pi$; $\rho' \to a_1\pi$		x	x	x	$\rho'(1700)$
$\bar{p}N \to \rho'\pi$; $\rho' \to h_1\pi$			x	x	
$\bar{p}N \to \rho'\pi$; $\rho' \to \pi^*\pi$		x	x	x	
$\bar{p}N \to \pi^*\sigma$;		x	x	x	$\pi^*(1300)$
$\bar{p}N \to \pi^*\rho$;			x	x	$\pi^*(1300)$
$\bar{p}N \to f_2\pi$; $f_2 \to \sigma\sigma$	x	x	x	x	$f_2(1270)$,
$\bar{p}N \to f_2\pi$; $f_2 \to \rho\rho$			x	x	$f_2(1565)$
$\bar{p}N \to f_2\pi$; $f_2 \to a_2\pi$			x	x	
$\bar{p}N \to a_1\sigma$;		x	x	x	$a_1(1260)$
$\bar{p}N \to a_1\rho$;			x	x	$a_1(1260)$
$\bar{p}N \to h_1\rho$;				x	$h_1(1170)$
$\bar{p}N \to a_2\rho$;			x	x	$a_2(1320)$

the $\sigma\pi$-decay mode. An indication for this observation is already visible in the data. In fig.3c the $\pi^-\pi^0\pi^0$ invariant mass a high mass shoulder is seen which is absent in the $3\pi^0$ invariant mass (fig.3d). We find a mass and width for the $\pi^*(1300)$ of m=(1400 ± 40)MeV and Γ=(275 ± 50)MeV.

2.2 The f_0 states

The $\pi^-4\pi^0$-data set is the most sensitive to scalar contributions since there is only one combination to form a f_0 and since the number of intermediate states possible is smaller than in the data sets involving more charged pions (see tab.1). We first tried to describe the data using the amplitudes listed in tab.1 but only one f_0 state decaying into $4\pi^0$. Fig.4a,b shows the data for the $4\pi^0$ invariant mass and the best fit with one f_0 and with 2 f_0 states. Both the peak region and the high mass edge of the peak are poorly described with only one scalar state. This is significantly improved with the introduction of a second scalar state. The fit to the mass and width of these two states optimize at $m = 1400 \pm 30\,\mathrm{MeV/c^2}$ and $\Gamma = 251 \pm 45\,\mathrm{MeV/c^2}$ for

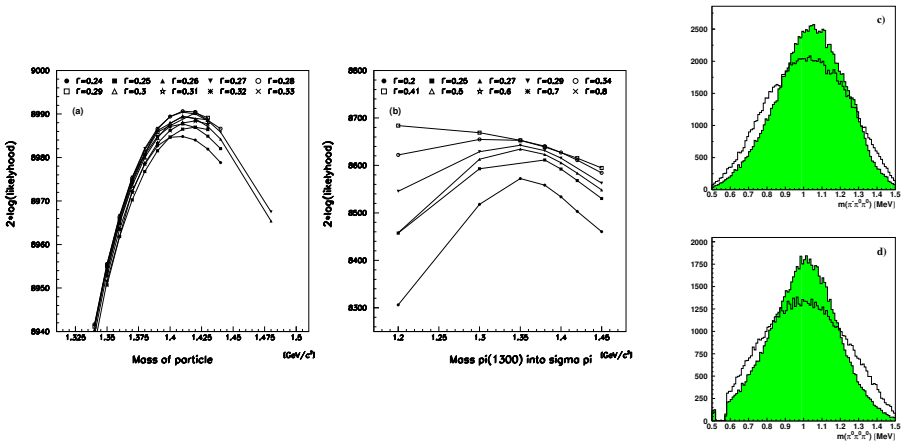

Figure 3: *Scan of the π^* mass and width; a) only the decay $\pi^* \to \rho\pi$ allowed, b) only $\sigma\pi$-decay mode. The different curves indicate different widths of the scanned particle, the best description of the data is reached at a maximum in log($\mathcal{L}$).*
c) $\pi^-\pi^0\pi^0$, d) $\pi^0\pi^0\pi^0$ invariant mass of the $\pi^- 4\pi^0$ data set. The shaded distribution shows the data, the curve the phase space.

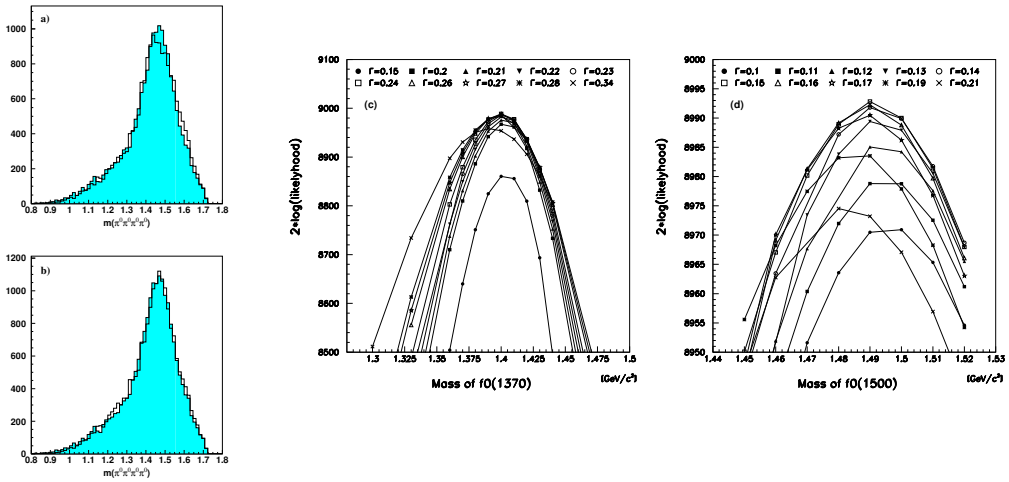

Figure 4: *a),b) The $4\pi^0$ invariant mass from the $\pi^- 4\pi^0$ final state. The points with error bars are the data. The line shows the best fit with only one f_0 (a) and two f_0 states allowed (b).*
Scan of c) $f_0(1370)$ mass and width, d) $f_0(1500)$ mass and width. All amplitudes given in table1 have been introduced.

the lighter state and to $m = 1490 \pm 30\,\mathrm{MeV/c^2}$ and $\Gamma = 150 \pm 40\,\mathrm{MeV/c^2}$ for the heavier state. The maxima in ln(L) of the two states are shown in figure 4c,d. As visible in fig.4d the width of the more massive state is consistent with 130 MeV. This value leads to a better consistency with the $\bar{p}p \to 5\pi^0$ data and is in a close agreement with earlier publications. Therefore we impose this value in all further fits. Introducing an $f_0(1770)$ state [12], with $m = 1770\,\mathrm{MeV/c^2}$ and $\Gamma = 170\,\mathrm{MeV/c^2}$ leads to a small improvement in $2\ln\mathcal{L}$, and a slightly better description of the data in the high mass $4\pi^0$ region. But since this state lies outside of the available phase space it is not possible to determine its mass and width in this analysis. In addition, the introduction of this state tends to destabilize the remainder of the fit. Thus we are unable to definitively say if it is present or not.

Concerning the decay modes of the scalar states we found, summarizing the results obtained from the fits to all data sets, the $f_0(1370)$ to decay strongly into $\sigma\sigma$ and $\rho\rho$; there are also indications for a small decay into $\pi^*\pi$ and $a_1\pi$. For the $f_0(1500)$ we find a $\sigma\sigma$ and $\pi^*\pi$ decay mode, $\rho\rho$ is not favoured. Fig 5. shows the final fit for the $\pi^- 4\pi^0$ data set. Masses and widths of the scalar states as well as their relative

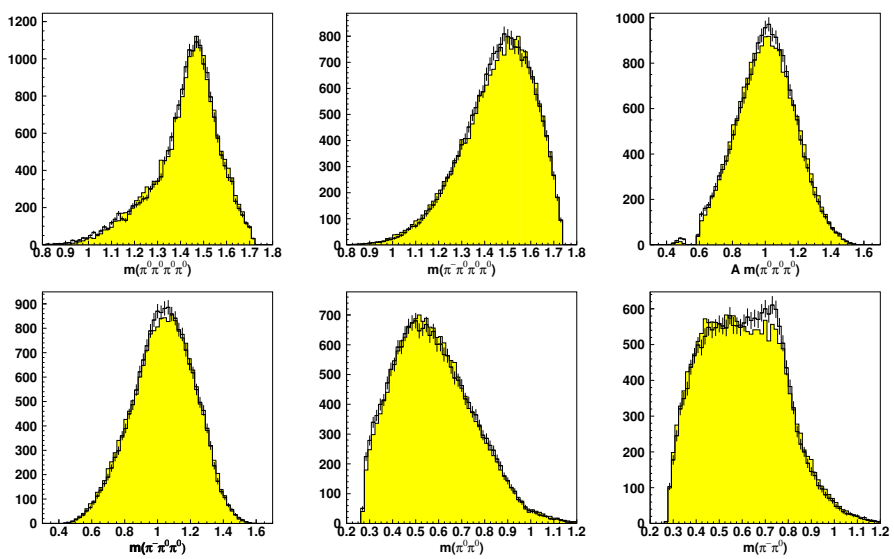

Figure 5: *A comparison between the data, (points with error bars), and the fit, (shaded region), to the $\pi^- 4\pi^0$ data set. The effect of the η–anti-cut in the $3\pi^0$–invariant mass is clearly visible.*

production strength determined from the $\pi^- 4\pi^0$ data set can now be introduced in the $5\pi^0$ data set. The result for this fit with only one free parameter – the relative phase between the two f_0's – is shown in fig. 6. The fit nicely agrees with the data.

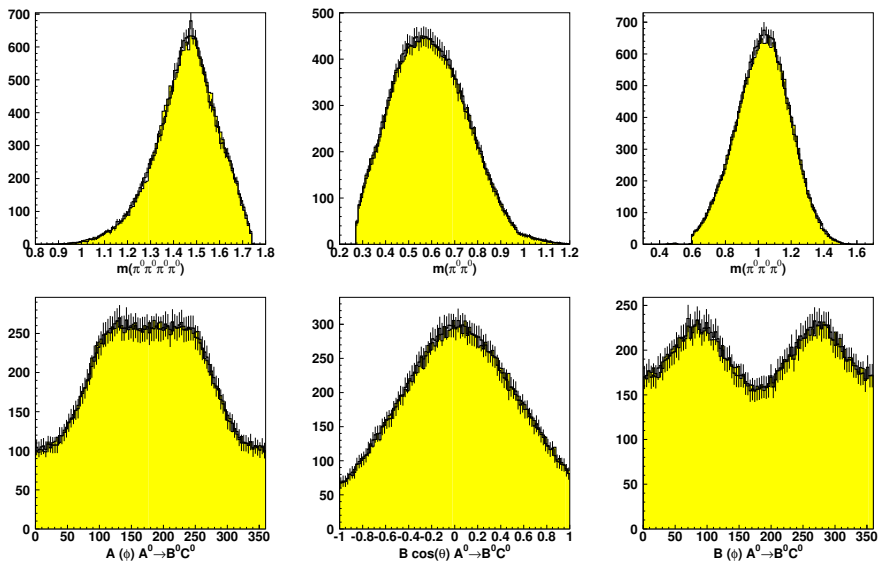

Figure 6: *Quality of the fit to the* $5\pi^0$ *data. Masses, widths and the relative production strength of the particles have been fixed to the results found in fitting the* $\pi^-4\pi^0$ *data set. Data: line with error bars, fit: shaded area.*

From this data we derived the following branching ratios:

$$\begin{aligned} \mathrm{BR}\,(\bar{p}p \to f_0(1370)\pi^0 \to (\pi\pi)_S(\pi\pi)_S\pi^0 \to 5\pi^0) &= (28.4 \pm 6) \cdot 10^{-4} \\ \mathrm{BR}\,(\bar{p}p \to f_0(1500)\pi^0 \to (\pi\pi)_S(\pi\pi)_S\pi^0 \to 5\pi^0) &= (2.8 \pm 1.5) \cdot 10^{-4} \end{aligned}$$

These can be combined with an earlier analysis on $3\pi^0$ final states to obtain information on the relative branching ratios. Using [13]

$$\begin{aligned} \mathrm{BR}\left[\bar{p}p \to f_0(1370)\pi^0, f_0(1370) \to \pi^0\pi^0\right] &= (6.4 \pm 2.4) \times 10^{-4}\,, \\ \mathrm{BR}\left[\bar{p}p \to f_0(1500)\pi^0, f_0(1500) \to \pi^0\pi^0\right] &= (8.2 \pm 0.9) \times 10^{-4}\,, \end{aligned}$$

This shows that the 4π decay of the $f_0(1370)$ clearly dominates especially if taking into account that the resonance has a $\rho\rho$ decay mode which is even stronger than its decay into $\sigma\sigma$. Also the $f_0(1500)$ decay into 4 pions is very important. In both cases the isospin Clebsch-Gordans for other charged states have to be taken into account. The description of the $\pi^+2\pi^-2\pi^0$ data set reached is shown in fig. 7. The $\bar{p}p \to \pi^+\pi^-3\pi^0$ data was used only for consistency checks because much more initial states are possible in this reaction.

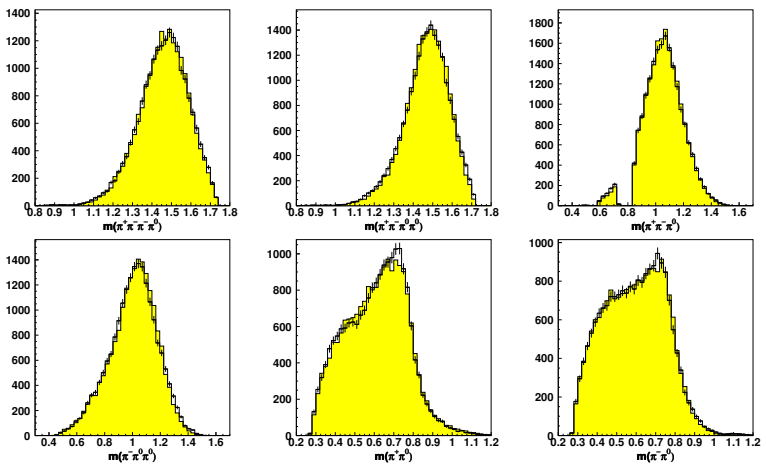

Figure 7: *A comparison between the data, (points with error bars), and the fit, (shaded region), to the* $\pi^+2\pi^-2\pi^0$ *data set.*

3 Summary

The analysis of the reactions $\bar{p}p \to 5\pi^0$, $\bar{p}d \to \pi^- 4\pi^0 p_{spectator}$, $\bar{p}p \to \pi^+\pi^- 3\pi^0$ and $\bar{p}d \to \pi^+ 2\pi^- 2\pi^0 p_{spectator}$ has shown that the scalar intensity plays a very important role. Two scalar states are definitely needed to describe the data, the $f_0(1370)$ with $m = 1400 \pm 30\,\mathrm{MeV/c^2}$, $\Gamma = 251 \pm 45\,\mathrm{MeV/c^2}$ and the $f_0(1500)$ with mass and width compatible with previous findings. The 4π decay of the $f_0(1370)$ clearly dominates the all other observed decay modes. We also find a mass and width for the $\pi^*(1300)$ of $m = 1400 \pm 40\,\mathrm{MeV/c^2}$ and $\Gamma = 275 \pm 50\,\mathrm{MeV/c^2}$, and that its $\rho\pi$ decay mode is at least 10 times stronger than its $\sigma\pi$ decay.

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