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4π-decays of scalar and vector mesons

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Abstract. Two different $\bar{p}n$ annihilation modes, $\bar{p}n \to \pi^-4\pi^0$ and $\bar{p}n \to 2\pi^-2\pi^0\pi^+$, are used to study the 4π–decays of scalar and vector mesons. The data are dominated by 4π scalar isoscalar interactions. At least two states are needed, the $f_0(1370)$ and the $f_0(1500)$. The 4π–decay width of the $f_0(1370)$ is more than 6 times larger than the sum of all observed partial decay widths to two pseudoscalar mesons. The state has important couplings to $(\pi\pi)_S(\pi\pi)_S$ and to $\rho\rho$. The 4π-decays of the $f_0(1500)$ represent about half of its total width. The $\rho(1450)$ and the $\rho(1700)$ are observed in several 4π decay modes. The ratio of the 4π relative to the 2π decay of the $\rho(1450)$ is in contradiction to its proposed interpretation as a pure hybrid state but it suggests that it is not a pure 2^3S_1–state either. Our results favour the assignment of the $\rho(1700)$ as $^3D_1$ state, its interpretation as 3^3S_1-state is less plausible.

1 Introduction

The possibility that gluonic excitations of hadronic matter or of the QCD vacuum may exist is perhaps the most fascinating topic in hadron spectroscopy. In the absence of mixing with quarkonia, glueballs are bound states of only gluons. In lattice gauge theories the lightest glueball is predicted to have scalar quantum numbers and a mass of about $1.73\,\mathrm{GeV/c^2}$ [1]. The existence of more scalar isoscalar mesons than the quark model can host has led to speculations that a glueball has intruded into the spectrum of scalar quarkonia and mixes with them, thus producing the states observed in the mass range below $2\,\mathrm{GeV/c^2}$ [2,3]. Different mixing schemes e.g. [2,3] allow an explanation of the observed decays of the $f_0(1500)$ into two pseudoscalar mesons even though the glueball content of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are quite

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different in these models. Experimental information on decay modes for these states may be helpful for deciding which of these models is correct. Indeed, calculations exist which show that the determination of the different 4π decay modes might be crucial to shed light on this mixing scheme [4,5].

The situation is similar in the case of vector mesons. The question of interest is the existence of hybrids, or mesons in which the string mediating the interaction between quarks and antiquarks is excited. An isovector meson with exotic quantum numbers, $J^{PC} = 1^{-+}$, (the $\hat{\rho}$ (1400) or $\pi_1(1400)$), has been observed recently by E852 at BNL [6,7] and at CERN by Crystal Barrel [8,9]. If this state is a member of a nonet, it should be accompanied by an isoscalar partner, (the $\hat{\omega}$ or η_1) and such a state could have several decay modes into four pions.

Hybrids can also have non–exotic quantum numbers. Indeed, a nonet of $J^{PC} = 1^{--}$ hybrid mesons is expected in the 1.8 GeV/c^2 mass region [10]. These may mix with normal $\bar{q}q$ states. In the isovector sector, two excited states are known, the $\rho(1450)$ and $\rho(1700)$. There are speculations that one of these ρ-states may have a large hybrid content [11].

The ρ-states have been studied in different production mechanisms and are seen in several decay modes. Their 4π decay modes and the breakdown into intermediate resonances are of particular importance since the coupling to different resonances may provide decisive information on the internal structure of these states [12,13]. Most information on the 4π decays is presented in a review on e^+e^- and photoproduction data [14]. Both the $\rho(1450)$ and the $\rho(1700)$ have been observed in the reaction $\bar{p}d \to \pi^-2\pi^0 p_{\rm spectator}$ by their decays into $\pi^-\pi^0$ [16]. In this analysis, we study the two reactions

$$\bar{p}n \to \pi^+2\pi^-2\pi^0 \tag{1}$$

$$\bar{p}n \to \pi^-4\pi^0 \tag{2}$$

to observe scalar and vector states in their different 4π decays produced recoiling against a pion. The analysis examines the 4π decays in terms of an isobar decomposition using intermediate resonances. Annihilation on (quasi-free) neutrons is ensured by stopping antiprotons in liquid D_2 and applying a tight cut on the momentum of the spectator proton ($p_p < 100 \mathrm{MeV}/c$).

2 Data and data reduction

The Crystal Barrel is a detector with a close-to-4π acceptance for both charged particles and photons. A 200 MeV/c $\bar{p}$ beam stops in a liquid deuterium target at the center of the detector. The target is surrounded by a silicon strip vertex detector used for triggering (SVX) and a 23–layer cylindrical drift chamber (JDC). The momentum resolution for charged particles varies from $\delta p/p = 2.0\%$ at 0.2 GeV/c up to $\delta p/p = 6.5\%$ at 1 GeV/c. The JDC is in turn surrounded by a 1380 crystal CsI(Tl) barrel calorimeter. The calorimeter covers polar angles between 12^0 and 168^0 degrees and 2π in azimuth. The useful acceptance for shower detection is 95% of 4π. Typical resolutions are σ_E/E =2.5% at 1 GeV, and $\sigma_{\phi,\theta} = 1.2^0$ with a minimum usable photon energy of 15 MeV. Further details can be found elsewhere [17].

The data selection for the 30 016 $\pi^-4\pi^0$ events of reaction (2) has been discussed in a preceding paper [18]. This analysis adds data from the $\pi^+2\pi^-2\pi^0$ final state from reaction (1) and describes a fit to the latter data set which is consistent with that of the former. These data stem from $\sim 6.5 \times 10^6$ triggered events which have been collected using a *three–prong* trigger. The trigger selects events with three hits in the SVX and one or two hits per track in the outer layer of the JDC. In addition to the triggered data, $\sim 1.3 \times 10^6$ minimum bias events are used to determine the branching fraction into this final state, and $\sim 1.1 \times 10^6$ Monte Carlo events were generated for normalization and acceptance corrections. The data are required to satisfy the following criteria:

– Exactly one positive and two negative charged tracks.
– Exactly four photons with energy above 20 MeV.
– For each electromagnetic shower due to a photon, the energy deposited in the central crystal should exceed 13 MeV. This cut removes spurious photons due to shower fluctuations.
– Events containing photons centered in the crystals adjacent to the beam pipe are rejected due to possible shower leakage.

Data surviving these cuts are submitted to a 1–constraint kinematic fit to the hypothesis $\bar{p}d \to \pi^+2\pi^-4\gamma$ plus an unseen proton. In a second step, a series of higher-constraint kinematic fits is performed in which the $\gamma\gamma$ pairs are constrained to be either π^0 or η. We then require the best hypothesis to be $\pi^+2\pi^-2\pi^0 p_{\rm spectator}$. Events are rejected if the confidence level of this fit is less than 10%. Additionally, all events with a spectator proton momentum larger than 100 MeV/c are rejected to select events which are consistent with $\bar{p}$ annihilation on a quasi–free neutron. From the 6.5 million triggered events, 46 629 survive all the cuts. For these events, we form the four $\pi^+\pi^-\pi^0$ invariant mass combinations and remove those events with at least one mass combination within ± 60 MeV/c^2 of the $\omega(782)$ mass or within ± 30 MeV/c^2 of the $\eta(548)$ mass, (see Fig. 1b). This yields 19 419 events from the *three prong* data set.

The branching fraction for reaction (1) is determined using minimum–bias data. The number of reconstructed events excluding $\bar{p}d \to \pi^-\pi^0\eta p$ and $\bar{p}d \to \pi^-\pi^0\omega p$, is $N_{5\pi} = 742$ from a sample of $N_{mb} = 1\,293\,538$ minimum bias events. The reconstruction efficiency, $\varepsilon_{mc} = (1.9 \pm 0.1)\%$ includes the decay of π^0, ($\mathrm{BR}(\pi^0 \to \gamma\gamma) = 0.98798 \pm 0.00032$). In addition, there is a correction for antiprotons which do not annihilate in the target, $\varepsilon_1 = 0.956 \pm 0.025$. Excluding the contributions from $\bar{p}d \to \pi^-\pi^0\eta p$ and $\bar{p}d \to \pi^-\pi^0\omega p$, we find the rate as given in (3). In [18], it has been found that the rate for reaction (2) is as given in (4).

$$\mathrm{BR}(\bar{p}d \to \pi^+2\pi^-2\pi^0 p) = \frac{N_{5\pi}}{\varepsilon_{mc} \cdot \varepsilon_1 \cdot N_{mb}}$$

$$= (3.15 \pm 0.47)\% \quad (3)$$

$$\mathrm{BR}(\bar{p}d \to \pi^- 4\pi^0 p) = (0.67 \pm 0.10)\% \quad (4)$$

3 The partial wave analysis

3.1 Formalism

The partial wave analysis of the data is performed in the helicity formalism [20] in terms of the isobar model [21]. The initial $\bar{p}n$ system is assumed to decay into the 5π final state via a series of quasi two–body decays via intermediate resonances. The data are fitted using an unbinned maximum likelihood fit to the full 8–dimensional phase space of the 5π final state to maximize the quantity $2\ln\mathcal{L}$. The initial $\bar{p}n$ state is pure isospin 1, and the G–parity of the final state is negative. This limits the initial $\bar{p}n$ atomic states to be ${}^1\mathrm{S}_0$, ${}^3\mathrm{P}_0$, ${}^3\mathrm{P}_1$ or ${}^3\mathrm{P}_2$. In this analysis, we restrict the initial state to be ${}^1\mathrm{S}_0$. We do expect that initial P–state contributions play a role but their inclusion adds a large number of poorly determined parameters, and the fit is unable to separate individual initial state contributions. The consistency between the results on reaction (2) and on $\bar{p}p \to 5\pi^0$ (with much smaller contributions from P-states) serves as justification of this approximation. We note that scalar and pseudoscalar mesons do not carry any information on the initial $\bar{p}N$-state. Vector mesons contribute only a few %; and their largest rate comes from annihilation from the ${}^1\mathrm{S}_0$–state [22]. The influence of P-wave amplitudes on the parameters of other resonances has been tested by introducing different amplitudes, it was found to be negligible.

We impose consistency in masses and widths of intermediate resonances which are common to both reactions, (1) and (2). The partial wave analysis proceeds in the same fashion as in [18], we summarize here the key points only.

We look for decays of scalar isoscalar states into $(\pi\pi)_S$ $(\pi\pi)_S$, $\rho\rho$, $\pi(1300)\pi$ and into $a_1(1260)\pi$, and for decays of the vector isovector states into $h_1(1170)\pi$, $a_1(1260)\pi$, $\pi(1300)\pi$, $\rho(\pi\pi)_S$ and into $\rho\rho$. The $h_1(1170)$, $a_1(1260)$ and $\pi(1300)$ are observed via their $\rho\pi$ decay mode. The decay of the $a_1(1260)$ and the $\pi(1300)$ into $(\pi\pi)_S\pi$ has been tested and was found to be negligible. The $(\pi\pi)_S$ (which we call σ) is the scalar isoscalar $\pi\pi$ interaction; it has been parameterized to agree with the data in [23,24].

The production and decay of the first resonance is parameterized by a production vector $\hat{F} = \beta \cdot \hat{F}'$; $\hat{F}'$ is given in (5). Pairs of daughter particles the resonance decays into are represented as ab, cd while l_{ab} and l_{cd} represent the relative angular momentum between them. The partial width into the daughters ab is Γ_{ab}; $B_{l_{ab}}$ is a Blatt–Weisskopf factor involving the relative angular momentum between the daughters, and $\rho_{ab}(m)$ is a phase space factor for the decay evaluated at the mass m. See reference [25] for a more detailed discussion.

$$\hat{F}'_{(ab)} = \frac{m_0\sqrt{\frac{\Gamma_0\Gamma_{ab}}{\rho_{ab}(m_0)}}\,B_{l_{ab}}}{m_0^2 - m^2 - im_0\left[\frac{\rho_{ab}(m)}{\rho_{ab}(m_0)}\Gamma_{ab}\cdot B^2_{l_{ab}} + \frac{\rho_{cd}(m)}{\rho_{cd}(m_0)}\Gamma_{cd}\cdot B^2_{l_{cd}} + \cdots\right]} \quad (5)$$

The $\hat{F}'$ vector is multiplied by $\hat{T}'_1$ and $\hat{T}'_2$ which describe the decays of daughter and granddaughter particles, by the product isospin Clebsch–Gordan coefficients CG and the helicity amplitude $\mathcal{H}$ describing the angular distributions for the amplitude. $\hat{T}'$ has the same form as $\hat{F}'$ given in (5). B_{L_k} describes the centrifugal barrier of the production of the first resonance. The amplitudes are then coherently summed as in (6). The sum is extended over all allowed combinations of π's with appropriate Clebsch–Gordan coefficients, based on the ordering of the π's. The ordering is important because of sign changes of the Clebsch–Gordan coefficients.

$$\mathcal{A}_k = \sum_{j=1}^{\text{decay channels}} \sum_{i=1}^{\#\text{combinations}} \mathrm{CG_i} \cdot \mathrm{\hat{F}'_{A_{ij}}} \mathrm{\hat{T}'_{B_{ij}}} \mathrm{\hat{T}'_{C_{ij}}} \mathcal{H}_\mathrm{j} \mathrm{B_{L_k}} \quad (6)$$

The summation in (6) extends over the possible combinations which contribute to a given reaction chain k like, e.g., $\bar{p}n \to f_0\pi^- \to \rho^+\rho^-\pi^-$ and subsequent decays into 5 pions. Further reaction chains like $\bar{p}n \to \rho^- a_1(1260)$ are taken into account by summation over all interfering amplitudes:

$$\mathcal{A}_{\text{total}} = \sum_k \beta_k \mathcal{A}_k \quad (7)$$

If $\hat{T}'$ is replaced by a $\hat{T}$-matrix (numerator in (5) changed to $m_0 \cdot \Gamma_1/\rho_1^0 \cdot B^2_{L1}$) assuming that the second step resonances are produced by scattering, the influence on the resonance masses and widths is found to be negligible. The effects on the branching ratios are within the errors given. Contributions of amplitudes including a B^2_L not equal one in the T-matrices are slightly decreased using this parametrisation.

Fits to the data are made to extract masses, widths, ratios of partial decay widths Γ_{ij} and the complex production strengths β_k of contributing resonances.

3.2 Resonance parameters

Masses and widths of the two scalar resonances found from reaction (1) are compatible with those reported in [18] which we use as fixed values in further fits. For the $\rho(1450)$ we find in both reactions (1) and (2) a broad shallow maximum consistent with the PDG–values and [16] and a best value of $m = 1435 \pm 40\,\mathrm{MeV/c^2}$ and $\Gamma = 325 \pm 100\,\mathrm{MeV/c^2}$. The $\rho(1700)$ parameters cannot be deduced from our fits. The final results are averaged over several fits using the values of masses and widths as given in Table 1.

3.3 Fit results

The rates given in Table 2 list the fractional contributions to the specific final states; they are not corrected for unseen decay modes. The significance of individual contributions can be seen from the change in $2\ln\mathcal{L}$ when a contribution is removed from the fit. Of course, new parameters

Table 1. The masses and widths of the $\rho(1450)$ and $\rho(1700)$ (in MeV/c^2) used in these fits

Particle	Mass	Width	Mass	Width	Mass	Width
	PDG [26]		CBAR [16]		This Analysis	
$\rho(1450)$	1465 ± 25	310 ± 60	1411 ± 14	343 ± 20	1435 ± 40	325 ± 100
$\rho(1700)$	1700 ± 20	235 ± 50	1780 ± 37	275 ± 45		

always lead to an improved likelihood. We estimate that a minimum of ~ 15 per parameter is required to indicate the presence of a further decay mode. The number of parameters per amplitude is in general two. An exception is the $\bar{p}N \to \rho'\pi \to \rho\rho\pi$ amplitude where the two ρ spins can sum up to different spin states.

We now describe how amplitudes are introduced and how their importance for further fits is determined. The fit starts with a minimal set of parameters which are derived from the best fit to reaction (2) from reference [18]. These are the reactions with entries in the last column of Table 2. For convenience we also reproduce the fractional contributions to reaction (2) and $\Delta(2\ln\mathcal{L})$ when a contribution is removed. To this first fit we add successively further amplitudes. Of course, the likelihood change for a given reaction is large when few amplitudes are used; with increasing number of amplitudes likelihood changes become smaller.

Adding $\rho^+\rho^-$ decays of the $f_0(1370)$ increases $2\ln\mathcal{L}$ by 3427, and for the $f_0(1500)$ by an additional 70. The former is highly significant, the latter significant. The addition of the amplitude for $\bar{p}n \to \pi(1300)\rho$ increases $2\ln\mathcal{L}$ by 489, that for $\bar{p}n \to a_1(1260)\rho$ by an additional 221. Allowing both the $\rho(1450)$ and $\rho(1700)$ to decay to $h_1(1170)\pi$ increases $2\ln\mathcal{L}$ by 359. The addition of $f_2(1270)$ and $f_2(1565)$ – allowed to decay to $\rho^+\rho^-$ and to $a_2(1320)\pi$ – increases $2\ln\mathcal{L}$ by 1011. Allowing $\pi(1300)\pi$ decays of the $f_0(1370)$ brings an improvement of 223 in $2\ln\mathcal{L}$, the inclusion of this decay for the $f_0(1500)$ improves the fit by 43. The amplitudes for $\bar{p}n \to h_1(1170)\rho$ and $\bar{p}n \to a_2(1320)\rho$ make a negligible improvement. We have also considered the $\rho\rho$ decays of both the $\rho(1450)$ and $\rho(1700)$, and find significant improvements, with $\Delta(2\ln\mathcal{L}) = 80$ and 257, respectively. Finally we did allow the $a_1\pi$-decay mode of the $f_0(1500)$ and the $f_0(1370)$. This improves the fit again by 51 and by 116. From the fit with all amplitudes of Table 2 introduced we remove single amplitudes to test their significance. The changes in $2\ln\mathcal{L}$ are given in columns 6 and 8. The errors in the contributions given in Table 2 are determined by calculating the rates if amplitudes are excluded from the fit which lead to a change in $2\ln\mathcal{L}$ of less than 100.

In these fits, PDG values for masses and widths of the $a_1(1260)$ and the $h_1(1170)$ were used. When varied, the data proved to be insensitive to variations within reasonable limits. The $a_1(1260)$ and $\pi(1300)$ might also decay to $(\pi\pi)_S\pi$ in addition to $\rho\pi$. These decays have been tested, but they bring no significant improvement to the description and have been dropped from the fits. As in [18] the $\pi(1300)$ is found to decay dominantly into $\rho\pi$ ($\Gamma_{\sigma\pi} < 15\% \cdot \Gamma_{\rho\pi}$).

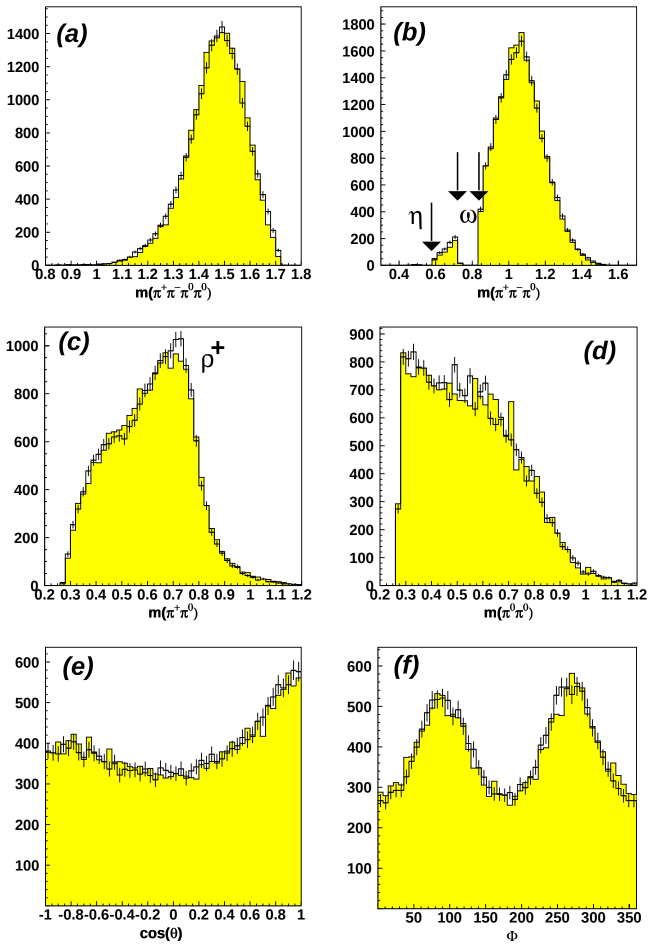

Fig. 1a–f. A comparison of the best fit (solid) and the data (points with error bars) for a selection of projections and angular distributions

A comparison of several projections of the data and the fit are shown in Fig. 1. While there are small deviations near the peak of the $\rho(770)$ meson, (**c**), overall the fit looks very good. Attempts to improve the fit in the region of the ρ by adding more decay chains failed. The addition of any incoherent amplitude including a ρ e.g. from an initial P–state improves the description of the ρ peak and yields only a small contribution from that initial P–state, with negligible changes in the other results.

Table 2. Results of the best fit to the $\bar{p}n \to \pi^+ 2\pi^- 2\pi^0$ and $\pi^- 4\pi^0$ data. All masses and widths are held fixed in this analysis. The rates given refer to the quoted observed reaction chains. $\Delta(2\ln\mathcal{L})$ shows the change in $2\ln(\mathcal{L})$ when this particular contribution is removed from the fit

Amplitude	Mass	Width	Decay Pattern	$\bar{p}n \to \pi^+ 2\pi^- 2\pi^0$	$\Delta(2ln\mathcal{L})$	$\bar{p}n \to \pi^- 4\pi^0$	$\Delta(2ln\mathcal{L})$
$\bar{p}n \to f_0(1370)\pi^-$	1395	275	$f_0 \to (\pi^+\pi^-)_s(\pi^0\pi^0)_s$	$16.0 \pm 2.5\%$	1418		
			$f_0 \to (\pi^0\pi^0)_s(\pi^0\pi^0)_s$			$68.9 \pm 4.0\%$	7625
			$f_0 \to \rho^+\rho^-$	$19.0 \pm 3.5\%$	267		
			$f_0 \to \pi^*\pi$	$12.7 \pm 4.0\%$	218		
			$f_0 \to a_1\pi$	$4.3 \pm 1.2\%$	116		
$\bar{p}n \to f_0(1500)\pi^-$	1490	130	$f_0 \to (\pi^+\pi^-)_s(\pi^0\pi^0)_s$	$1.5 \pm 0.3\%$	153		
			$f_0 \to (\pi^0\pi^0)_s(\pi^0\pi^0)_s$			$6.7 \pm 0.7\%$	2065
			$f_0 \to \rho^+\rho^-$	$1.7 \pm 1.0\%$	36		
			$f_0 \to \pi^*\pi$	$6.7 \pm 2.8\%$	132		
			$f_0 \to a_1\pi$	$1.6 \pm 0.5\%$	68		
$\bar{p}n \to \pi(1300)(\pi\pi)_s$	1375	268	$\pi \to \rho\pi$	$5.3 \pm 1.0\%$	948	$5.4 \pm 0.4\%$	1022
$\bar{p}n \to \pi(1300)\rho$	1375	268	$\pi \to \rho\pi$	$0.4 \pm 0.1\%$	85		
$\bar{p}n \to \rho(1450)\pi$	1435	325	$\rho \to \rho\sigma$	$0.3 \pm 0.3\%$	18	$1.4 \pm 0.3\%$	59
			$\rho \to a_1\pi$	$0.8 \pm 0.2\%$	70	$1.3 \pm 0.3\%$	44
			$\rho \to \pi^*\pi$	$1.3 \pm 0.4\%$	156	$0.9 \pm 0.2\%$	83
			$\rho \to h_1\pi$	$0.4 \pm 0.2\%$	28		
			$\rho \to \rho\rho$	$0.6 \pm 0.2\%$	130		
$\bar{p}n \to \rho(1700)\pi$	1700	235	$\rho \to \rho\sigma$	$1.1 \pm 0.2\%$	58	$4.7 \pm 0.7\%$	154
			$\rho \to a_1\pi$	$0.3 \pm 0.3\%$	19	$5.1 \pm 0.9\%$	220
			$\rho \to \pi^*\pi$	$2.5 \pm 0.7\%$	262	$0.3 \pm 0.3\%$	29
			$\rho \to h_1\pi$	$1.9 \pm 0.6\%$	192		
			$\rho \to \rho\rho$	$1.0 \pm 0.2\%$	229		
$\bar{p}n \to a_1(1260)\rho$	1230	400	$a_1 \to \rho\pi$	$5.9 \pm 0.7\%$	430		
$\bar{p}n \to f_2(1270)\pi^-$	1275	185	$f_2 \to \rho^+\rho^-$	$1.7 \pm 0.6\%$	304		
$\bar{p}n \to f_2(1565)\pi^-$	1560	255	$f_2 \to \rho^+\rho^-$, $a_2\pi$	$1.1 \pm 0.3\%$	381		

3.4 Search for an exotic $(I^G)J^{PC} = (0^+)1^{-+}$ state

In addition to the amplitudes listed in Table 2 we have searched for a possible contribution from an isoscalar companion of the isovector $J^{PC} = 1^{-+}$ state. We introduced this state, η_1, to be degenerate in mass and width with the isovector state, ($m = 1400\,\mathrm{MeV/c^2}$, $\Gamma = 310\,\mathrm{MeV/c^2}$ [8]) and we allow decays into $a_1(1260)\pi$, $\pi(1300)\pi$, and $\rho\rho$. The introduction of these amplitudes leads to an improvement in $2\ln(\mathcal{L})$ of 208 for 8 additional parameters but the contribution to reaction (1) is less than 1%. If one excludes the $\rho'(1450)$ from the fit the contribution for the exotic wave goes up to 2%. The decay proceeds as before basically via $\rho\rho$, $2\ln(\mathcal{L})$ gets worse by 370. When mass and width of the η_1 are left free no maximum in $2\ln(\mathcal{L})$ in found, therefore we do not claim evidence for an η_1. An upper limit for the production of the exotic η_1 with $m = 1400\,\mathrm{MeV/c^2}$, $\Gamma = 310\,\mathrm{MeV/c^2}$ of

$$\mathrm{BR}(\bar{p}d \to \eta_1\pi^- p \to (a_1\pi,\, \pi^*\pi,\, \rho\rho)\pi^- p \to 5\pi p) < 11\cdot 10^{-4} \quad (8)$$

can be determined. The π^* is used as shorthand for the $\pi(1300)$.

4 Interpretation

4.1 Branching ratios

Table 2 lists the decay chains contributing to reactions (1) and (2) and gives fractional contributions to the final states when interference effects with the recoiling meson are neglected. We differentiate between three types of interference effects, all of which are important in $\bar{p}N$ annihilation into five pions. In a *clean* environment such as e^+e^- annihilation, only self interference between the decay particles are important. Under particular circumstances, there can also be interference between different reaction chains, but this is mostly small, (like e.g. in ρ–ω interference). In $\bar{p}N$ annihilation, there are of course self-interference effects within the decay particles of a resonance, there is interference between different reaction chains and there is in addition interference with the recoil meson. This latter term is not present in formation experiments.

The treatment of interference effects in determination of branching ratios is not unambiguous. Nevertheless we

Table 3. Ratios of branching ratios for $f_0(1370)$ and $f_0(1500)$ decays. The ratios are normalized to their total 4π or 2π width, respectively. The branching ratios in the upper half of the table are determined from $\bar{p}n$ annihilation, the ratios in the lower half from $\bar{p}p$ annihilation. The branching ratios for decays into two pseudoscalar mesons are taken from [30–32]

		$\sigma\sigma/4\pi$	$\rho\rho/4\pi$	$\pi(1300)\pi/4\pi$	$a_1(1260)\pi/4\pi$
LD_2	$f_0(1370)$	0.51±0.09	0.26±0.07	0.17±0.06	0.06±0.02
	$f_0(1500)$	0.26±0.07	0.13±0.08	0.50±0.25	0.12±0.05
		$\eta\eta/\pi\pi$	$\eta\eta'/\pi\pi$	$K\bar{K}/\pi\pi$	
LH_2	$f_0(1370)$	0.02±0.01		(0.37±0.16) to (0.98±0.42)	
	$f_0(1500)$	0.08±0.01	0.07±0.01	0.18±0.03	

calculate fractional contributions and branching ratios and define precisely the method we use. We attempt to calculate what the contributions would be if the state were produced in a formation experiment. The fraction of the final state to which a particular amplitude contributes is determined by integrating the fit amplitude over the phase space. All amplitudes involving different recoiling mesons are treated as incoherent (even though they are of course treated as coherent in the fits). If, for example, there are two possible recoil π^0, then the branching fraction is computed using (9) while the fit is performed using (10). As an example, 90% of the reaction $\bar{p}p \to 5\pi^0$ is assigned to the chain $\bar{p}p \to \pi^0 f_0(1370) \to 5\pi^0$. But using (9), we find that about 50% of the intensity is created by interference effects between the recoil π^0 and the four π^0's coming from the $f_0(1370)$.

$$\mathrm{BR} \sim \mid \mathcal{A}(X\pi_1^0) \mid^2 + \mid \mathcal{A}(X\pi_2^0) \mid^2 \tag{9}$$

$$\mid \mathcal{A} \mid^2 \sim \mid \mathcal{A}(X\pi_1^0) + \mathcal{A}(X\pi_2^0) \mid^2 \tag{10}$$

The values given in Table 2 need to be corrected for the unseen reaction $\bar{p}n \to 2\pi^+3\pi^-$, this is not unambiguous. Naively this could be done using isospin symmetry on the level of intensities by multiplying e.g. the rate $f_0 \to \sigma\sigma \to 4\pi^0$ by a factor 9 or the rate $f_0 \to \sigma\sigma \to \pi^+\pi^-2\pi^0$ by $\frac{9}{4}$ to get the total $f_0 \to \sigma\sigma \to 4\pi$ rate. On the other hand, isospin symmetry represents a symmetry on the level of amplitudes; interference effects within the decay of a particle may lead to violation of isospin symmetry at the level of intensities and branching ratios. The importance of such interference effects can be seen by comparing the branching ratios in (11) and (12). These should be equal if isospin symmetry would be a good symmetry at the level of branching ratios, but instead they differ by a factor of 3.7.

$$9 \times BR(\bar{p}n \to f_0(1370)\pi^- \to \sigma\sigma\pi^- \to 4\pi^0\pi^-) \approx 4.16 \cdot 10^{-2} \tag{11}$$

$$\frac{9}{4} \times BR(\bar{p}n \to f_0(1370)\pi^- \to \sigma\sigma\pi^- \to \pi^+\pi^-2\pi^0\pi^-) \approx 1.14 \cdot 10^{-2} \tag{12}$$

This comparison emphasizes the importance of interference effects when fractional contributions are evaluated. Nevertheless we try to estimate the contributions which one would expect from the reaction $\bar{p}n \to 2\pi^+3\pi^-$. This is unambiguous for decay sequences which contribute only to reaction (1) or (2). If a decay sequence is observed in both channels we proceed as follows. In the case of isoscalar resonances decaying into $\sigma\sigma$ the Clebsch–Gordan weight is 1/9 for $4\pi^0$ and 4/9 for $2\pi^0\pi^+\pi^-$ and $2\pi^+2\pi^-$. We multiply the sum of the two contributions by the inverse Clebsch–Gordan weight 9/5. Isoscalar resonances decaying into $\rho\rho$ do not contribute to reaction (2), the missing contribution from $2\pi^+2\pi^-$ is then half of the rate observed in (1). The same procedure is also used for the isovector states taking the correct isospin Clebsch–Gordan coefficiens into account.

4.2 The scalar resonances

The data on reaction (1) are dominated by the $f_0(1370)$ decaying into $\rho^+\rho^-$ and $(\pi^+\pi^-)_S(\pi^0\pi^0)_S$, in addition its decays into $\pi^*\pi$ and $a_1\pi$ are observed. Important contributions are also found for $f_0(1500)$ into $(\pi^+\pi^-)_S(\pi^0\pi^0)_S$ and $\pi^*\pi$. After taking into account the Clebsch–Gordan coefficients the ratios given in the upper half of Table 3 are evaluated. For completeness we collect in the lower half results from previous analyses on the decays of the f_0-states into 2 pseudoscalar mesons [30–32].

To provide a link between $\bar{p}p$ and $\bar{p}n$ annihilation, the $\sigma\sigma$ decay of the $f_0(1370)$ and the $f_0(1500)$ can be used. In LH_2 [18] the ratios

$$\frac{f_0(1370)\to\sigma\sigma\to4\pi^0}{f_0(1370)\to2\pi^0} = 4.4 \pm 1.9 \quad \text{and} \tag{13}$$

$$\frac{f_0(1500)\to\sigma\sigma\to4\pi^0}{f_0(1500)\to2\pi^0} = 0.34 \pm 0.19 \tag{14}$$

were determined. In LD_2 the following ratios have been measured:

$$\frac{f_0(1370)\to\sigma\sigma\to4\pi^0}{f_0(1370)\to\sigma\sigma\to4\pi} = 0.27 \pm 0.06 \quad \text{and} \tag{15}$$

$$\frac{f_0(1500)\to\sigma\sigma\to4\pi^0}{f_0(1500)\to\sigma\sigma\to4\pi} = 0.27 \pm 0.07 \tag{16}$$

The fractional contributions (given in Table 3) can be normalized using (13–16) and their sum can be identified with

Table 4. Partial widths Γ_i (in MeV) of $f_0(1370)$ and $f_0(1500)$ for decays into two pseudoscalar particles and into four pions assuming that all decay modes are observed. The error of the total width is included in the errors for the partial widths. The pseudoscalar branching ratios to calculate the partial widths are taken from [30–32]

	Γ_{tot}	$\sigma\sigma$	$\rho\rho$	$\pi(1300)\pi$	$a_1\pi$
		$\pi\pi$	$\eta\eta$	$\eta\eta\prime$	$K\bar{K}$
$f_0(1370)$	275 ± 55	120.5 ± 45.2	62.2 ± 28.8	41.6 ± 22.0	14.1 ± 7.2
		21.7 ± 9.9	0.41 ± 0.27		(7.9 ± 2.7) to (21.2 ± 7.2)
$f_0(1500)$	130 ± 30	18.6 ± 12.5	8.9 ± 8.2	35.5 ± 29.2	8.6 ± 6.6
		44.1 ± 15.3	3.4 ± 1.2	2.9 ± 1.0	8.1 ± 2.8

Table 5. Decay rates of the $\rho(1450)$ and $\rho(1700)$, normalized to all observed 4π decays (not including $\pi\omega$)

Particle	$a_1(1260)\pi/4\pi$	$h_1(1170)\pi/4\pi$	$\pi(1300)\pi/4\pi$	$\rho\rho/4\pi$	$\rho(\pi\pi)_s/4\pi$	$2\pi/4\pi$
$\rho(1450)$	0.27 ± 0.08	0.08 ± 0.04	0.37 ± 0.13	0.11 ± 0.05	0.17 ± 0.09	0.37 ± 0.10
$\rho(1700)$	0.16 ± 0.05	0.17 ± 0.06	0.30 ± 0.10	0.09 ± 0.03	0.28 ± 0.06	0.16 ± 0.04

the total width assuming that all decay modes of the states have been measured. Thus partial widths of the two scalar states are obtained which are listed in Table 4. The 4π-decays of the $f_0(1370)$ are the dominant decay modes; in particular the two decays into $\sigma\sigma$ and into $\rho\rho$ are very strong. Also for the $f_0(1500)$ we find that the 4π-decays are important, they cover about half of all decays. The WA102 collaboration reports that the $f_0(1500)$ decays into $\rho\rho$ and $\sigma\sigma$ while the $f_0(1370)$ decays dominantly into $\rho\rho$ [27]. This is incompatible with our findings, especially the $4\pi^0$ invariant mass of the $\bar{p}n \to \pi^-4\pi^0$ and $\bar{p}p \to 5\pi^0$ data set [18] cannot possibly be explained by the $f_0(1500)$ alone. The implications of this discrepancy for the scalar states were discussed in [28].

4.3 The vector states

The fractional contributions of the vector states $\rho(1450)$ and $\rho(1700)$ to $\bar{p}n$ annihilation after correcting for the unseen contribution to $2\pi^+3\pi^-$ are collected in Table 5. It should be mentioned that the different ρ' amplitudes in the $\bar{p}d \to \pi^+2\pi^-2\pi^0$ data set contribute only on the 1% level with the consequence of large errors. Furthermore, the big number of amplitudes necessary may lead to uncertainties in their determination. That this may cause problems can be seen by a comparison of the $\rho(1700) \to a_1\pi$ and $\rho(1700) \to \pi(1300)\pi$ amplitudes measured in the two data sets (see Table 2). While the $\rho(1700) \to a_1\pi$ amplitude is quite important in the $\pi^-4\pi^0$ data set, it is not in $\pi^+2\pi^-2\pi^0$. In decays into $\pi(1300)\pi$ the situation is reversed. If one gives more credit to the description of the $\pi^-4\pi^0$ data set where the fit depends only on a reduced number of parameters, the importance of the $a_1\pi$ decay of the $\rho(1700)$ is increased and that for its $\pi(1300)\pi$ decay is decreased compared to the numbers given in Table 5.

In addition it should be noted that the ρ decays into 4π do not include decays into $\pi\omega$ but only the decay modes mentioned.

In [16], the $\bar{p}n$ annihilation frequency for production of $\rho(1450)$ and $\rho(1700)$ and their decay into $\pi\pi$ was determined. From [16] and this analysis we obtain

$$\frac{\rho(1450) \to 2\pi}{\rho(1450) \to 4\pi\ (\pi\omega\,\text{not included})} = 0.37 \pm 0.10 \quad (17)$$

$$\frac{\rho(1700) \to 2\pi}{\rho(1700) \to 4\pi\ (\pi\omega\,\text{not included})} = 0.16 \pm 0.04 \quad (18)$$

We do not give partial decay widths since ρ' decays into $\pi\omega$ can not yet be included; preliminary results on these decays have been reported in [29].

The results can be compared to the predictions of reference [12,13] as shown in Table 6.

Before doing so, we emphasize again how problematic this comparison is: the ρ' states have small contributions to the reactions we have analysed and the errors are consequently large. Calculations give the two mesons to which ρ'-states decay, data provide information on the final state; this may be different since scattering between the decay products of the two primarily produced mesons into a different meson pair may have occurred.

If the $\rho(1450)$ is a 2^3S_1-state, it should have a large coupling to $\pi\pi$, a large coupling to $\pi\omega$ (not yet known) and small couplings to 4π. This is in conflict with data. The isobars within the 4π-modes, e.g. the πa_1-decay relative to $\pi\pi$, are also in conflict with the predictions for a 2^3S_1-state. If the $\rho(1450)$ is a hybrid, it should have a very large decay width to πa_1. Based on this argument, the data do not exclude a sizable hybrid component. The decays into $\pi\pi$ and $\pi(1300)\pi$ are on the other hand in contradiction with the hybrid interpretation and also the 2π over 4π ratio is not in agreement with this interpretation.

Table 6. Expected decay widths (in MeV) for ρ mesons as computed in the $^3P_0$ model [12] and in the flux-tube model [13] (last row). NC= not calculated

Decay Mode	$\pi\pi$	$\pi\omega$	πa_2	πa_1	πh_1	$\rho\rho$	$\pi(1300)\pi$	$\rho(\pi\pi)_s$
$2^3S_1\rho(1465)$	74	122	0	3	1	0	NC	NC
$1^3D_1\rho(1700)$	48	35	2	134	124	0	14	NC
$3^3S_1\rho(1900)$	1	5	46	26	32	70	16	NC
Hybrid-$\rho(\sim 1500)$	0	$5-10$	~ 0	140	0	NC	0	NC

Distinctive are the predictions for $\pi\omega$: a hybrid should (nearly) not, a 2^3S_1-state should strongly couple to $\pi\omega$.

The $\rho(1700)$ couples to πh_1 and πa_1 as well as to $\pi\pi$, decay modes which are suggestive for a 1^3D_1 interpretation. Especially its coupling to $\pi\pi$ favours the 1^3D_1-interpretation and disfavours the possibility that it is a 3^3S_1-state. It is hence likely, that the $\rho(1700)$ is the 1^3D_1-state. Decays into $\pi\omega$ – if observed – would substantiate this assignment.

If a hybrid intrudes the 1^{--}-spectrum in this mass region mixing can occur. This could possibly explain the observed rates. On the other hand one would then expect three states to be present in the mass region below 1800 MeV. Additional experimental information on the $\omega\pi$-decay of these states is highly desirable to clarify the experimental situation.

5 Summary

We have analysed two antiproton-neutron annihilation modes into five pions and found that they proceed dominantly via production of scalar resonances. We find very strong contributions from the $f_0(1370)$ and a significant fraction of $f_0(1500)$. The isobar contributions to their decays, $\sigma\sigma, \rho\rho, a_1(1260)\pi$ and $\pi(1300)\pi$, were determined. Including previous data on decays into two pseudoscalar mesons, their total widths was expanded into a sum of partial widths.

The $\rho(1450)$ and $\rho(1700)$ are observed to decay into different 4π isobars. Since contributions from $\pi\omega$, $\rho\eta$ and $K\bar{K}$ are not yet determined, only relative decay rates could be derived from the data and no partial decay widths. These ratios suggest that the $\rho(1700)$ may be a conventional 1^3D_1-state. The $4\pi/2\pi$-ratio of the $\rho(1450)$ is incompatible with it being a pure 2^3S_1-state. Its coupling to $a_1\pi$ allows a sizable hybrid component; its $\pi\pi$-decay mode is larger than would be expected for a hybrid.

We have searched for the isoscalar state η_1 with exotic quantum numbers $J^{PC} = 1^{-+}$. If the $\pi_1(1400)$ is a hybrid, it should have an isoscalar companion at about the same mass. We do not find positive evidence for its existence.

The $\pi(1300)$ is observed in its direct production jointly with a ρ or $(\pi\pi)_S$ and in the $\pi(1300)\pi$-decay mode of the scalar and vector resonances; it is found to decay dominantly into $\rho\pi$ ($\Gamma_{\sigma\pi} < 15\% \cdot \Gamma_{\rho\pi}$)

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