$\bar{p}d$-annihilation at rest into $\pi^+\pi^-\pi^-p_{spectator}$

Crystal Barrel Collaboration

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A study of antiproton annihilation in liquid deuterium into $\pi^+\pi^-\pi^-$ and a spectator proton is presented. For a long time this reaction resisted a description by final state interactions which is surprising (and disturbing) given the success of the final state interaction model in other annihilation reactions. It is shown that the introduction of $\rho(1450)$ is essential to get a reasonable description of the measured Dalitz plot. This resonance was never tried in previous attempts to understand this data. A possible isospin-2-$\pi\pi$ S-wave contribution was tested, but no evidence was found for such a contribution.

The study of antiproton annihilation on protons or neutrons has revealed interesting results on meson spectroscopy and has given new insights into the dynamics of the process. Early bubble chamber experiments demonstrated strong ρ production in $\bar{p}p$ annihilation at rest into $\pi^+\pi^-\pi^0$ with approximately equal rates for ϱ^+, ϱ^- and ϱ^0 [1]. Since annihilation into $\varrho^0\pi^0$ is forbidden from initial states with isospin $I = 1$, the result implied a strong suppression of $\rho\pi$ annihilations from the isovector component of the annihilating $\bar{p}p$ system. This effect is known as the ρ-puzzle in the literature [2]. Antiproton annihilation on neutrons provides a pure isospin $I = 1$ initial system and has distinct advantages in comparison to $\bar{p}p$ annihilation since the N$\bar{\text{N}}$ isoscalar contribution is missing. Studies of the reaction $\bar{p}n \to \pi^-\pi^0\pi^0$ demonstrated evidence for two radial excitations of the ρ [3]. This successful analysis has stimulated the analysis of the reaction $\bar{p}n \to 2\pi^-\pi^+$ which we present here. Formerly, there were rather unsatisfying attempts to understand this reaction [4–7]. The failure of the description within the isobar model by two-body $\pi\pi$ final-state interactions [5] led Lovelace [6] to an attempt to explain the data within the Veneziano model [8]. The absence of events at the center of the Dalitz plot was explained by zeros of the production amplitude, an interpretation which was seemingly supported by the observation of a series of further holes in the same reaction but at a momentum of 1.2 GeV/c [9]. In a systematic discussion of 3-pion

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annihilation at rest and in flight, Kalogeropoulos et al. concluded however that the hole structure is a property of annihilation at rest with no significant hole structure present in in-flight annihilations [7]. The statistics on the reaction $\bar{p}n \rightarrow 2\pi^-\pi^+$ in that analysis was augmented to 5512 events and peaks were marked at the positions of the ρ, the $f_2(1270)$ and even at that of the $f_0(1500)$. But a partial wave analysis was not attempted, and the description of the data stayed at a descriptive level with *castles, towers* and *holes*. The hole structure in the $2\pi^-\pi^+$ data was used as a support for the hypothesis that the annihilation amplitude might have a strong energy-dependence. Such an energy dependence emerged from an analysis of $\bar{p}p$ annihilation at rest into $3\pi^0$ using a N/D method [10].

As the data on $\bar{p}n \rightarrow 2\pi^-\pi^+$ have so far resisted all attempts at a consistent description, in spite of the low statistics of bubble chamber experiments, it seems to be important to demonstrate that the isobar model - which was successfully used in the analysis of $\bar{p}n \rightarrow \pi^-\pi^0\pi^0$ - gives also a consistent interpretation of $2\pi^-\pi^+$ annihilation.

The data have been collected with the Crystal Barrel detector at LEAR. The detector has been described in detail elsewhere [11]; only a short summary will be given here. A 200 MeV/c $\bar{p}$ beam stopped in the liquid deuterium target at the center of the detector. In 1994, the former inner tracking device, a pair of cylindrical multiwire proportional chambers (PWC's), was replaced by a silicon vertex detector (SVTX). This vertex detector was placed as close as possible around the target; its main purpose was the possibility to trigger on K^0_s decays. A spin-off effect was a precise tracking point close to the target which gives an improvement in momentum resolution [12]. The main tracking device for charged particles was a cylindrical drift-chamber (JDC) with 23 layers. Together with the SVTX, a momentum resolution of $\delta p/p = 4.5\%$ at 1 GeV/c was obtained. The JDC is surrounded by a barrel consisting of 1380 CsI(Tl) crystals, pointing towards the center of the target. The CsI calorimeter covers the polar angles between 12° and 168° with full coverage in azimuth. The useful acceptance for shower detection is $0.95 \times 4\pi$ sr. Typical photon energy resolutions are $\sigma_E/sqrt[4]E = 2.5\%$ at 1 GeV, and $\sigma_{\Phi,\Theta} = 1.2°$ in both the polar and azimuthal angles. In the selection of the final state presented here, the calorimeter was used as a veto against additional photons.

The data for the present analysis have been taken with a *three-prong trigger* requiring three hits in the outer JDC-layers. This trigger setup was used because we are interested in events with a proton spectator momentum below 100 MeV/c and protons in this momentum range cannot escape the target. The following off-line selection criteria were applied :

– Exactly two negative charged and one positive charged track in the JDC,
– no additional photons in the calorimeter,

– Energy and momentum conservation by constraining the "missing mass" to be consistent with the mass of the spectator proton $p_{spectator}$:
$| E_{\rm tot}^2 - p_{\rm tot}{}^2 - m_{proton}{}^2 | \leq 0.5 \ \mathrm{GeV}^2/c^4$

Data surviving these cuts underwent a kinematic fit to the $\bar{p}d{\rightarrow}\pi^-\pi^-\pi^+ p_{spectator}$ hypothesis (1C fit) Events have been rejected if the confidence level was below 10% or $p_{spectator}$ was above 100 MeV/c in momentum. The partial wave analysis which follows is not affected by varying the cut on spectator momentum up to 150 MeV/c^2. We have found no evidence for pionic interactions with the spectator proton (e.g. by formation of $\Delta(1232)$) in this momentum range. From the 6.5 million triggered events, we have assigned 35,689 events to the reaction

$$\bar{p}n \ \rightarrow \ \pi^+\pi^-\pi^- \ (p_{spectator} \ < \ 100\,\mathrm{MeV}/c).$$

The branching ratio for the reaction was derived from minimum bias data, requiring an antiproton stop in the target but no specific final state.

A Monte Carlo simulation, based on the CERN program package GEANT, was used to derive the detection efficiency. We find that the branching ratio for $\bar{p}d$ annihilations at rest into $\pi^-\pi^-\pi^+$ plus any (also non-spectator) proton is

$$BR(\bar{p}d{\rightarrow}\pi^-\pi^-\pi^+ \ plus \ proton) = (1.1 \pm 0.1)\%. \tag{1}$$

The $\pi^+\pi^-\pi^-$ Dalitz plot is presented in Fig. 1, the $\pi^+\pi^-$ and $\pi^-\pi^-$ invariant mass distributions in Figure 2. Contamination from other channels, determined using the Monte Carlo, is below 1.0% and distributed smoothly over the Dalitz plot.

The most prominent structure in the Dalitz plot is seen at low $\pi^-\pi^-$invariant masses, marked with an arrow in figure 1. Formerly, this structure was interpreted as evidence for a possible I=2 contribution [4], but attempts to get a reasonable fit failed. It will be shown later that this structure can be well described with $f_2(1275)$ and $\rho(1450)$. Because of the absence of strong $\rho(770)$ production from $I = 1$ initial states, the two bands of the $\varrho^0(770)$ are visible only weakly. At high $\pi^+\pi^-$masses an enhancement of events is seen; a partial wave analysis is needed to disentangle the possible contributions of scalar, vector and tensor resonances in this kinematic region. A second prominent feature of this final state is the hole in the middle of the Dalitz plot. This feature can be seen in all 3π Dalitz plots with self-interfering $\pi\pi$ S-waves like $3\pi^0$ [13] , $\pi^+\pi^+\pi^-$ [14] and $\pi^-\pi^-\pi^+$. Final states with only one combination for the creation of a $\pi\pi$ S-wave amplitude like $\pi^-\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ do not show this behaviour.

Annihilation may occur from $\bar{p}d$ atomic S-states with $J^P = 1/2^-, 3/2^-$ or

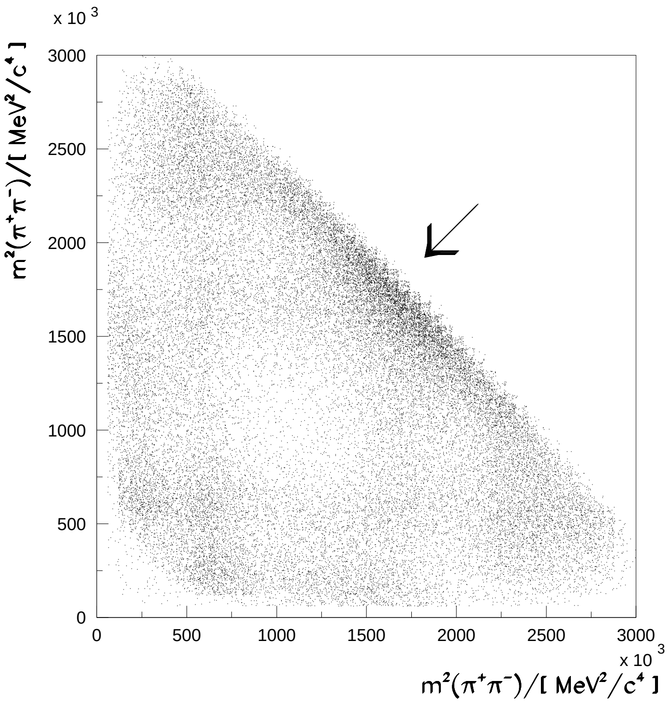

Fig. 1. $\pi^-\pi^-\pi^+$ Dalitz plot ($p_{spectator} \leq$ 100 MeV/c). For the partial wave analysis this plot is corrected with a smooth acceptance function. The arrow shows the most prominent structure, where the analysis found interference from $f_2(1270)$, $\rho(1450)$ and $f_0(1370)$.

from P-states with $J^P = 1/2^+, 3/2^+$ or $5/2^+$ in the present case. Final states of the present channel may be described by wave functions which are products of (a) $\bar{p}n$ eigenstates $^1S_0$, $^3P_1$ and $^3P_2$ and (b) spectator protons. The latter may have $L = 0, j = 1/2$ or $L = 1$ with $j = 1/2, 3/2$. Providing one integrates over all directions (and spin substates) of the spectator proton, it may be shown that all interferences between $\bar{p}n$ eigenstates disappear. Consequently the cross section may be expressed as the incoherent sum of cross sections to $\bar{p}n$ final states $^1S_0$, $^3P_1$ and $^3P_2$.

The partial wave analysis adopts the isobar model in P-vector approach. Details of the formalism can be found in [16]. For the $\pi\pi$ P-wave we use a 1-channel K-matrix, thereby guaranteeing unitary amplitudes in case of overlapping resonances. Angular distributions are described by the Zemach formalism [17]. Contributions of the $\pi\pi$ P- and D-wave are allowed from $^1S_0$, $^3P_1$ and $^3P_2$, whereas the $\pi\pi$ S-wave is restricted to $^1S_0$ and $^3P_1$ initial states by angular momentum and G-parity conservation.

Analogous to the analysis of the $\pi^-\pi^0\pi^0$ final state, $\pi\pi$ S-, P- and D-wave interactions contribute to the $\pi^-\pi^-\pi^+$ final state. It was shown in [3] that for the $\pi\pi$ S- and D-waves a fixed pole-structure from the analysis of $\bar{p}p \to 3\pi^0$[13]

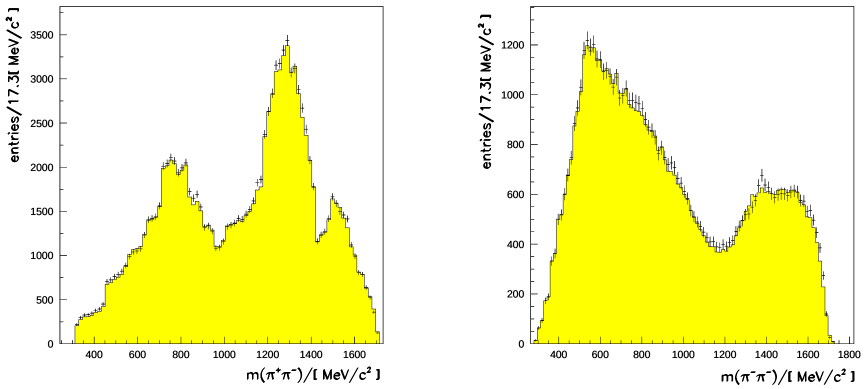

Fig. 2. $\pi^-\pi^+$ and $\pi^-\pi^-$ mass distribution. The data are plotted with error bars and the result of the best fit is overlayed.

Table 1
Masses and widths of $\pi\pi$ P-wave mesons used in the fit

Meson	Mass (MeV/c^2)	Width (MeV/c^2)
$\rho^0(770)$	763.7	152.8
$\rho^0(1450)$	1411	343
$\rho^0(1700)$	1780	275

can be imposed. The $3\pi^0$ final state is much more sensitive to the S- and D-waves, because of the large statistics and the absence of P-wave in $\pi^0\pi^0$ interactions. This S- and D-wave pole structure includes $f_0(980)$, $f_0(400-1200)$, $f_0(1370)$ and $f_0(1500)$ for the S-wave and $f_2(1270)$ and $f_2(1565)/AX$ for the D-wave. The $\pi\pi$ P-wave was taken from the $\pi^-\pi^0\pi^0$ analysis, which was sensitive to the detailed structure of these amplitudes. Table 1 shows the parameters of the resonances which contribute to the $\pi\pi$ P-wave in the first fit.

In this first attempt to describe the $\pi^-\pi^-\pi^+$data, only the production strength and the phases for the S-, P- and D-waves have been varied freely in the fit. The fit gets a χ^2 of 558 for 460 bins and 45 parameters. Comparison of data and fit shows no discrepancy in any region of the Dalitz plot.

The amplitudes show that the contribution of the $\pi\pi$ D-wave from $^3P_2$ is negligible. A fit without this contribution gets the same χ^2, but with 4 parameters less. Instead of using the $\pi\pi$ D-wave pole structure from [3], we tested the values for $f_2(1270)$ and $f_2(1565)$ as given in [15]. This fit gives a small improvement in χ^2 of 7. The contribution of the $^1S_0$ initial state is 60.5% and the contribution of $^3P_1$ and $^3P_2$ is 26.8% and 12.7%, respectively.

Fitting with two $\pi\pi$ P-wave poles ($\rho(770)$ and $\rho(1450)$, masses and widths from [3]) we found a χ^2 of 565. Thus we cannot claim the existence of the $\rho(1700)$ in this data. Varying masses and widths of the two ρ's freely in the fit, χ^2 improves by 12 units. The $\rho(1450)$ mass was fitted at 1368 MeV/c^2 and the width was determined to be 374 MeV/c^2. The $\rho(770)$ was found at 758.6 MeV/c^2, with a width of 159.2 MeV/c^2. The $\pi^+\pi^-$projection in figure 2(a) shows that that the line shape of the $\rho(770)$ could be influenced by possible $\rho-\omega$ mixing. Because of the minor improvement in χ^2 in fits using free masses and width of the $\pi\pi$ P-wave we conclude that the present data set is not sensitive to the precise pole positions of the $\pi\pi$ P-wave. Hence we adopt the fitted parameters from [3] (shown in table 1) for the further analysis.

As a next check, we omit the $\rho(1450)$ pole in the analysis. With only $\rho(770)$ and $\rho(1700)$, we get an unsatisfactory description of the Dalitz plot structures, manifested in the extremely bad χ^2 of 1019. Figure 3 shows the χ^2-distribution in the Dalitz plot for $|\ \chi^2\ | \geq 4$. Striking features are visible in the region where $f_2(1270)$ and $\rho(1450)$ interfere. With no $\rho(1450)$ we fail to reproduce the largest enhancement observed in the Dalitz plot. This is also the reason that previous attempts to understand this reaction remained unsuccessful.

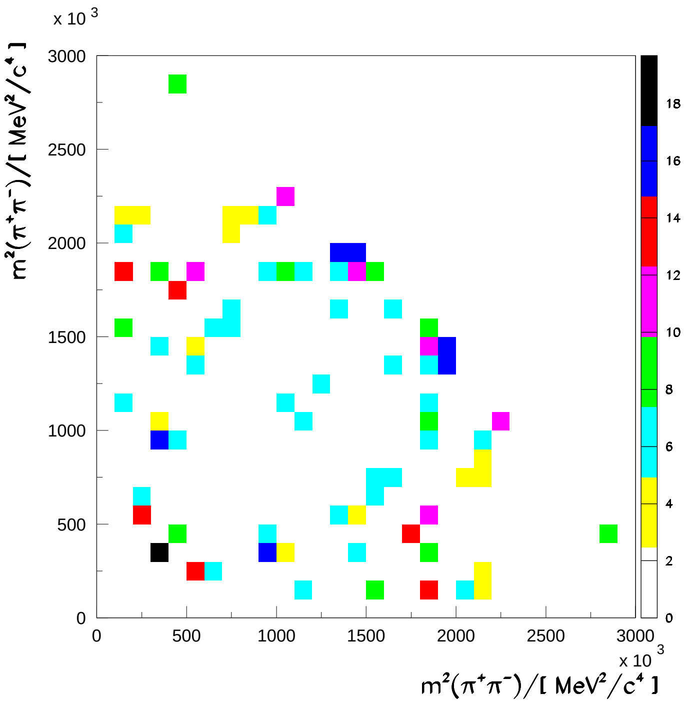

Fig. 3. χ^2-distribution ($|\ \chi^2\ | \geq 4$) for the fit without $\rho(1450)$.

In addition, we have investigated a possible $I = 2$ contribution in the $\pi^-\pi^-$amplitude. To our best fit we have added an $I = 2$ $\pi^-\pi^-$ S-wave with the phase motion taken from [18]. With this amplitude we get an improvement in χ^2 of -27, but without any phase-motion we get still a χ^2 improvement of -21. We therefore conclude that we have no evidence for a possible $I = 2$ $\pi\pi$ S-wave contribution in our data set but a contribution of the $I = 2$ $\pi^-\pi^-$-S-wave with a phase motion from [18] at the level of 1% cannot be excluded.

We have shown that $\bar{p}n$ annihilations to $\pi^-\pi^-\pi^+$ can be described in the isobar model with $\pi\pi$ S-, P- and D-wave contributions. The pole structure of a former analysis [3] is able to provide a very good fit to the measured data. It is shown that past attempts to understand this final state failed because of the missing contributions from $\rho(1450)$ and $\rho(1700)$. With these two additional resonances the data are well described. The data show no evidence for $I = 2$ contributions in the $\pi^-\pi^-$-S-wave. A hole structure in the annihilation amplitude is not required by the fit.

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