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New data on Δ^{++}-baryon production in $\bar{p}d$ annihilation at rest

OBELIX Collaboration

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Abstract

New experimental results on $\bar{p}d$ annihilation at rest into pions plus a high momentum proton in the final state are discussed. The data sample was collected using the OBELIX spectrometer at the LEAR facility (CERN). The annihilation probabilities, or more precisely the yields (Y) via channels $\bar{p}d \to 2\pi^-\pi^+\pi^0 p$ and $\bar{p}d \to 3\pi^-2\pi^+\pi^0 p$ with proton momenta

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$p > 400$ MeV/c have been measured for the first time: $Y = (93.2 \pm 1.6) \times 10^{-4}$ and $Y = (52.2 \pm 1.4) \times 10^{-4}$, respectively. The signal in the invariant mass distribution of the $p\pi^+$ system in the region of the well-known $\Delta^{++}(1232)$-isobar is clearly seen in reactions $\bar{p}d \to 2\pi^-\pi^+p$, $\bar{p}d \to 2\pi^-\pi^+\pi^0 p$, $\bar{p}d \to 3\pi^-2\pi^+p$ and $\bar{p}d \to 3\pi^-2\pi^+\pi^0 p$. The upper limit on reaction $\bar{p}\ (\Delta^-\Delta^{++}) \to 2\pi^-\pi^+p$ in the $p\bar{d}$ annihilation at rest, which could be interpreted as a manifestation of the $\Delta\Delta$ component of the deuteron, was found to be $Y \leq 6.5 \times 10^{-5}$ with a 90% confidence level.

1. Introduction

We report a measurement of the annihilation of antiprotons stopped in a deuterium gas target into three and five charged pions with a high momentum proton in the final state ($p_{\rm prot} > 400$ MeV/c), performed with the OBELIX spectrometer at LEAR (CERN). The following reactions were investigated:

$$\bar{p}\ d \longrightarrow 2\pi^-\pi^+p \qquad (1)$$

$$\bar{p}\ d \longrightarrow 2\pi^-\pi^+\pi^0\ p \qquad (2)$$

$$\bar{p}\ d \longrightarrow 3\pi^-2\pi^+p \qquad (3)$$

$$\bar{p}\ d \longrightarrow 3\pi^-2\pi^+\pi^0\ p \qquad (4)$$

The interest of these reactions is at least twofold. First, the study of πp rescattering in the final state. Deuterium data demonstrate a large tail of high energy protons, the deviation of experimental data from the deuteron wave function behaviour is dramatic [1]. There are some attempts to explain this effect via the πp rescattering, but if it is so, the signal from such a well-known product of rescattering as the Δ-isobar should be seen [2,3]. Till recently no experimental evidence of the existence, in the annihilation, of the Δ^{++}-isobar was found [4]. At present there is only one experimental observation of the Δ^{++} production in the $\bar{p}d$ annihilation at rest, which has been done by our collaboration [5]. We have found ≈ 200 Δ-isobars in the inclusive channel $\bar{p}d \to 2\pi^-\pi^+m\pi^0 p$ ($m = 0, 1, \ldots$). We have increased our statistics by more than 10 times, and it gives us the possibility to look for the Δ production not only in the inclusive reaction, but in the exclusive one, too. These measurements are very important for comparison with the predictions of various rescattering models [2,3,6,7].

Second point of the interest is the search for the $\Delta\Delta$ component of the deuteron. This information could be obtained from the analysis of the $\pi^-\pi^-$ system invariant mass distribution in the reaction $\bar{p}d \to 2\pi^-\pi^+p$. Indeed, according to some theoretical models a nucleons have a some probability to be internally excited and therefore be present as virtual isobars in every nucleus [8–12]. It is possible even at low energy due to the possibility of exciting internal nucleon degrees of freedom during close collisions of nucleons inside nuclei according to the process $N + N \to N + N^*(N^* + N^*) \to N + N$ involving intermediate N^*. It is expected, that the admixture probabilities of these exotic nuclear configurations are small, few percent or even less, due to the low nuclear density and rather high isobar-nucleon mass difference. For example in a deuteron the probability of $NN^*(1400)$ configuration can be less than 0.5% [13,14]. In the case of the deuteron the nuclei could also exist during some fraction of a time as a double-$\Delta(1232)$-isobar configuration, and the following annihilation process could be envisaged:

$$\bar{p}\ (\Delta^-\Delta^{++}) \longrightarrow (\bar{p}\Delta^-)\ \Delta^{++} \longrightarrow \pi^-\pi^-\pi^+\ p$$

This gives us the possibility to probe the internal deuteron structure in $\bar{p}d$ annihilation.

2. Experimental apparatus, trigger and data taking

The experiment has been carried out at an external beam line of the CERN Low Energy Antiproton Ring (LEAR). The description of the OBELIX spectrometer can be found elsewhere [15,16]. Here, we only give a short description of the detectors relevant to the present measurement.

The OBELIX spectrometer consists of three main sub-detectors arranged inside and around the Open-Axial Field Magnet (OAFM), providing a field of 0.5

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T over an open volume of about 3 m^3. These detectors are:
1) the Time-Of-Flight (TOF) system: two coaxial barrels of plastic scintillators for charged particle identification and triggering;
2) the Jet Drift Chamber (JDC) for tracking and particle identification by dE/dx measurement;
3) the High Angular Resolution Gamma Detector (HARGD): an electromagnetic calorimeter consisting of four modules made of layers of 3×4 m^2 Pb converter foils enclosed with planes of limited streamer tubes.

The length of the deuterium target was 72.0 cm along the beam axis and its radius was 12.0 cm. The distribution of annihilation vertices had $\sigma_z \approx 4.0$ cm and $\sigma_{xy} = 2.1$ cm, both an order of magnitude smaller than the respective dimensions of the target. The target was filled with gaseous deuterium at NTP.

The data used in this analysis were collected with a trigger on the charged prong multiplicity, requiring the following conditions:
- ≥ 4 hits in the inner barrel of the TOF system;
- ≥ 3 hits in the outer barrel of the TOF system.

The overall statistics comprises of 3.6×10^6 triggered events, plus a sample of 1.8×10^6 events collected with a minimum bias trigger, requiring only the disappearance of an incident antiproton in the target.

3. Data analysis

3.1. Event selection and annihilation probabilities

The TOF system of our spectrometer has been used to recognize the high momentum proton in the final state. Due to the design features of OBELIX it is only possible to reliably select protons with momenta $p > 400$ MeV/c, because protons with lower momenta are captured in various parts of the detector before they reach the second barrel of scintillating counters. In Fig. 1a one can see the proton and pion bands in the TOF system of OBELIX, in Fig. 1b the proton momentum distribution for reaction (2) is presented. All the distributions presented in this work are corrected for the acceptance of the experimental set-up. To select reactions (1)–(4) in the region of proton momenta $p > 400$ MeV/c the following selection criteria were applied:

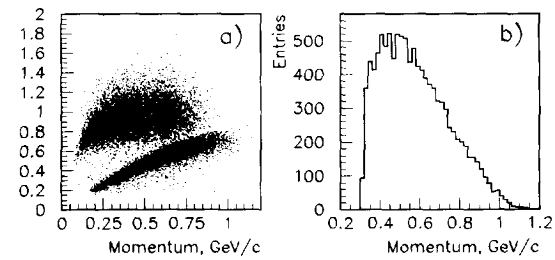

Fig. 1. (a) Proton and pion bands in the Time-Of-Flight system of OBELIX (the particle momentum mesured in the JDC). (b) Proton momentum distribution (protons selected by TOF) for the reaction (2) before the cut $p_{prot} > 400$ MeV/c.

- the number of tracks in the JDC was required to be 4 or 6;
- the total charge of the particles was required to be 0;
- the length of the track in the JDC was required to be greater than 25 cm;
- one particle in the event was required to be recognized by the TOF system as a proton with momentum > 400 MeV/c.

The total number of four-prong events that satisfied all these cuts was 28308 and the amount of six-prong events was 9294. Further, a 4C kinematical fit was done to select reactions (1), (3), and a 1C kinematical fit to extract reactions (2), (4) with χ^2 corresponding to a 90% confidence level for the selected channels (Fig. 2). The main background comes from reactions with an additional π^0-meson in the final state. To estimate the contamination from these reactions a Monte Carlo method was used. The high momentum proton in the final state was simulated with the Maxwell-Boltzmann distribution used with the temperature $E_0 =$ 98 MeV for four-prong reactions of the annihilation and $E_0 = 55$ MeV for six-prong events [1]. The Monte Carlo simulation was performed (by phase space) for each selected channel (1)–(4) as well as for the corresponding background reactions with one additional π^0 in the final state. The same number of generated events of both reactions (the main and the background) were processed in the same way as the experimental ones. The contamination has been calculated by the relation $C_{cont} = N_{back} \times W_{br}/N_{sig}$, where N_{back} is the number of events of the background reaction, satisfying all the cuts, N_{sig} is the same number for the main reaction, $W_{br} = Br_{back}/Br_{sig}$ is the weight of background events taken as the ratio between the annihilation branching ratios of the background (Br_{back}) and of the main

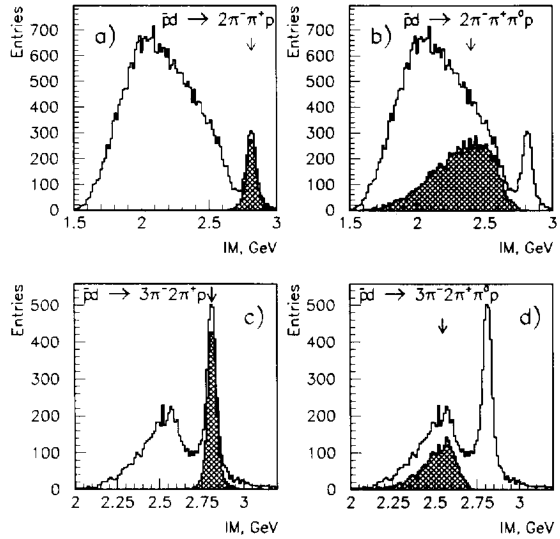

Fig. 2. (a), (b) The solid line shows the inclusive invariant mass distribution IM of four charged particles in data sample for four-prong events. The hatched histogram corresponds to reactions, selected by χ^2 corresponding to a 90% C.L. (c), (d) The same distribution as in (a), (b), but for six-prong data sample.

Table 1
The annihilation probabilities for reactions (1)–(4)

Final state	N_{ev}	ε_{MC}, %	Y, 10^{-4}
$2\pi^-\pi^-p$	1815	3.74 ± 0.02	$15.3 \pm 0.4 - 1.5$
$2\pi^-\pi^+\pi^0p$	9389	3.18 ± 0.02	$93.2 \pm 1.6 - 14.9$
$3\pi^-2\pi^+p$	2562	2.15 ± 0.02	$37.9 \pm 1.0 - 0.4$
$3\pi^-2\pi^+\pi^0p$	2420	1.46 ± 0.04	$52.2 \pm 1.5 - 0.1$

(Br_{sig}) reactions for proton momenta in the spectator region ($p < 200$ MeV/c), because its values are unknown for the high momentum proton region [17–19]. We assume that $W_{br}(p > 400 \text{ MeV}/c) \le W_{br}(p < 200 \text{ MeV}/c)$. The following estimates were obtained for the background contamination: $\le 10\%$, $\le 16\%$, $\le 1\%$ and $\le .2\%$ for reactions (1)–(4), respectively.

The annihilation probabilities have been measured for all the selected annihilation channels. In Table 1 the total numbers of events (N_{ev}) that passed all the cuts (including the cut on χ^2 for the selected hypotheses) are shown in the second column, the registration efficiencies in the third, and the corresponding annihilation probabilities (Y) in the fourth, the first error is statistical and the second is systematic (due to the contamination evaluated above). The total number of annihilated antiprotons is $N_{ann} = 3.9 \times 10^7\ \bar{p}$/target. The annihilation probability was calculated as $Y = N_{ev}/(\varepsilon_{MC} \times N_{ann})$. The registration efficiency ε_{MC} included the geometrical acceptance, the trigger efficiency, the detectors efficiencies and a correction for the annihilation into all neutrals.

The annihilation probabilities for reaction (1) and (3) are in good agreement with the values previously measured by OBELIX with lower statistics [5].

3.2. Δ^{++}-isobar production

The invariant mass distributions of the π^+p and π^-p systems for all the selected channels are shown in Figs. 3(a)–(d) and (e)–(h), respectively. Both particles were selected by TOF system of the OBELIX. As one can see, there is a clear peak in the region of the $\Delta^{++}(1232)$-isobar in the π^+p invariant mass, and, at the same time, no significant signal is present in the invariant mass of the π^-p system. This could reflect the fact that the $\Delta^{++}(1232)$ production cross section in π^+p scattering on free proton is nine times higher than the $\Delta^0(1232)$ production cross section in π^-p scattering. Moreover, the combinatorial background in the π^-p invariant mass is higher that in the π^+p one according to the number of opposite sing pions in the final state and the πp pairs in which the pion does not undergo rescattering contribute to smear out the structure of the isobar [6]. The invariant mass distribution of the π^+p system was approximated by the function:

$$F = A_1 \times BW(\Gamma_\Delta, M_\Delta, m) + A_2 \times \sum_{i=1,\dots,4} b_i \times m^{i-1} \qquad (5)$$

where BW is a Breit-Wigner function with mass M_Δ anu width Γ_Δ:

$$BW(\Gamma_\Delta, M_\Delta, m) = \frac{\Gamma_\Delta}{(m - M_\Delta)^2 + (\Gamma_\Delta/2)^2}. \qquad (6)$$

The parameters $A_1, A_2, \Gamma_\Delta, M_\Delta$ were released in the fit; the parameters of the polynomial, b_i, were taken from the fit of the π^-p system invariant mass distribution. The values of the Δ^{++} parameters yielded by this fit are shown in Table 2.

As one can see, the parameters of the Δ^{++} yielded by the fit coincide within the errors, except of one case,

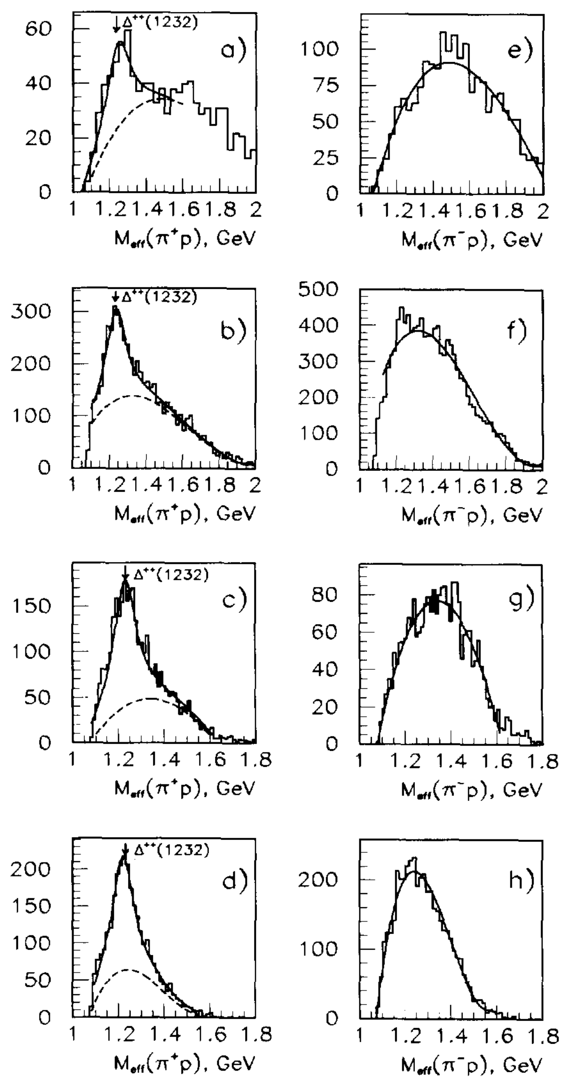

Fig. 3. (a)–(d) Invariant mass distribution of the $\pi^+ p$ system for reactions (1)–(4) fitted by Breit-Wigner function and fixed-shape polynomial background. (e)–(h) Invariant mass distribution of the $\pi^- p$ system for reactions (1)–(4) fitted by the third-order polynomial function.

Table 2
The values of the Δ^{++} parameters yielded by the fit

Reaction	$M_{\Delta^{++}}$, MeV	$\Gamma_{\Delta^{++}}$, MeV
$\bar{p}d \to 2\pi^-\pi^+p$	1244 ± 15	132 ± 13
$\bar{p}d \to 2\pi^-\pi^+\pi^0p$	1236 ± 4	129 ± 13
$\bar{p}d \to 3\pi^-2\pi^+p$	1229 ± 3	121 ± 6
$\bar{p}d \to 3\pi^-2\pi^+\pi^0p$	1220 ± 3	113 ± 10

Table 3
The fraction of events with the Δ^{++}-isobar in the final state for reactions (1)–(4)

Final state	Number of Δ^{++}	Fraction %	$< p_{\pi^+} >$ GeV/c
$2\pi^-\pi^+p$	183 ± 27	$18.0 \pm 2.6 \pm 1.7$	0.493
$2\pi^-\pi^+\pi^0p$	1621 ± 188	$30.1 \pm 3.4 \pm 1.5$	0.371
$3\pi^-2\pi^+p$	1772 ± 120	$52.0 \pm 3.5 \pm 2.7$	0.310
$3\pi^-2\pi^+\pi^0p$	1589 ± 163	$55.2 \pm 6.0 \pm 6.1$	0.253

with the PDG (Particle Data Group) parameters [20]. A slight shift downwards of the $\Delta(1232)$ peak is expected in the nuclei as a consequence of the nucleon Fermi motion [21]. For all the selected channels the number of events with a Δ^{++}-isobar in the final state has been calculated as the integral of the Breit-Wigner function (see second column in Table 3). The systematical error caused by the applied method of approximation has been estimated taking into account some uncertainties in the shape of the chosen background. For this purpose the invariant mass distribution of the π^+p system has been fitted by function (5) with fixed values of M_Δ and Γ_Δ, taken from PDG and free parameters of the polynomial function $b_1, \ldots, b_4$. The difference in the fraction of events with the Δ in the final state (third column in Table 3) obtained by applying two different approximation methods is given as a second, systematic error in Table 3 (the first error is statistical). The last column in Table 3 shows the average values of the π^+-mesons momentum distributions.

Thus, the fraction of events with the Δ^{++}-isobar increases with the pion multiplicity in the final state and reaches 55% for the reaction $\bar{p}d \to 3\pi^-2\pi^+\pi^0p$. This experimental fact is in good agreement with our understanding of rescattering as the origin of Δ in $\bar{p}d$ annihilation at rest. In fact, it has been well established in π^+p rescattering experiments that the maximum value of the Δ^{++}-isobar production cross section corresponds to a momentum of the incident π^+-meson ≈ 300 MeV/c. In Fig. 4 the π^+-meson momentum distributions are shown for all the selected annihilation channels. As one can see, in reaction (1) the average π^+-meson momentum is much higher than 300 MeV/c and the average π^+-meson momentum for reaction (2). At the same time, the average values of the π^+-meson momentum distributions for reactions (3) and (4) are close to the momentum correspond-

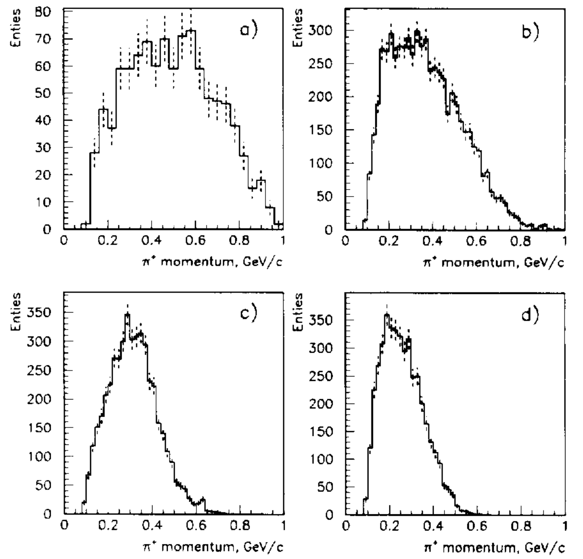

Fig. 4. (a)–(d) The π^+-meson momentum distributions for (1)–(4) channels of $\bar{p}d$ annihilation, respectively.

ing to the maximum of the Δ^{++} production cross section. The experimental evidence supports also the behaviours calculated in [22]. According to the rescattering model, the Δ^{++}-isobar excitation in the reaction $\bar{p}d \to 2\pi^-\pi^+p$ is weaker in respect to channels with higher pion multiplicity, due to the high average momentum of the pion that could preferably excite resonances above the Δ mass region. This could also explain the negligible signal in [4] spectra.

3.3. *Upper limit on the $\Delta\Delta$ component of the deuteron*

A non negligible $\Delta\Delta$ component is expected in the 6-quark model of the deuteron [23]. These $\Delta\Delta$ isobars are contained in the $|6q>$ part of the $|d>$ state and amount to 0.6%.

Attempts to detect the $\Delta\Delta$ configuration state of deuteron were made by many experimental groups [24–27]. As a rule, pion, photon, neutrino and proton beams of intermediate energy together with fixed target setups have been used for this purpose. These groups have tried to demonstrate the presence of N^* in nuclei by shaking loose an N^* that preexist in the nucleus acting as a spectator in some reactions. The main problem for such experiments was to distinguish between the signal from the internal N^* and the signal from another ones, produced by the conventional way, i.e. via rescattering. The experimental results, given as upper limits, are consistent with the 6q model prediction, ranging in (0.4–0.9)%.

A more simple, practically background free method to look for the $\Delta\Delta$-component of the deuteron is given by $\bar{p}d$ annihilation. As it was noted above, this information could be extracted from the analysis of the $\pi^-\pi^-$ system invariant mass distribution in the reaction $\bar{p}d \to 2\pi^-\pi^+p$. Indeed, if some fraction of time the deuteron could exist, due to the exciting of internal nucleon

degrees of freedom, for instance, as a double $\Delta(1232)$ configuration [10], the following annihilation process would be possible:

$$\bar{p}\,(\Delta^-\Delta^{++}) \longrightarrow (\bar{p}\Delta^-)\,\Delta^{++} \longrightarrow \pi^-\pi^-\pi^+\,p \qquad (7)$$

In this process an incoming $\bar{p}$ annihilates on the Δ^--isobar inside the deuteron into a $\pi^-\pi^-$ system and the spectator Δ^{++} decays into a π^+p system. It is worthwhile to stress that only annihilation processes give us such a possibility to search for the $\Delta\Delta$-component in the deuteron.

This reaction was investigated from the theoretical point of view. It was shown [28], that in the case of annihilation via channel (7) some peak in the high mass region of the $\pi^-\pi^-$ invariant mass distribution can be expected.

Moreover, and this is non trivial, in this case the width of the signal from $\bar{p}\ \Delta^- \to 2\pi^-$ annihilation (Δ^- is far off-mass-shell) could be in the (60–100) MeV interval, which makes it relatively easily recognized.

The main goal of our analysis was, due to the lack of statistics, to obtain only an upper limit on reaction (7). Fig. 5(a) shows the scatter plot for the invariant mass of the $\pi^-\pi^-$ system versus the invariant mass of the π^+p for $\bar{p}d$ annihilation via channel (1). There is some small enrichment in the upper part of the $\pi^-\pi^-$ invariant mass distribution, corresponding to the mass of the π^+p system in the $\Delta^{++}(1232)$ region, which cannot be explained within the framework of the two neucleon deuteron model and could be interpreted as a manifestation of the $\Delta\Delta$ configuration of the deuteron.

In Fig. 5(b) the invariant mass distribution of the $\pi^-\pi^-$ system in reaction (1) is shown. The solid line corresponds to all the selected events. The hatched histogram corresponds to the events with the invari-

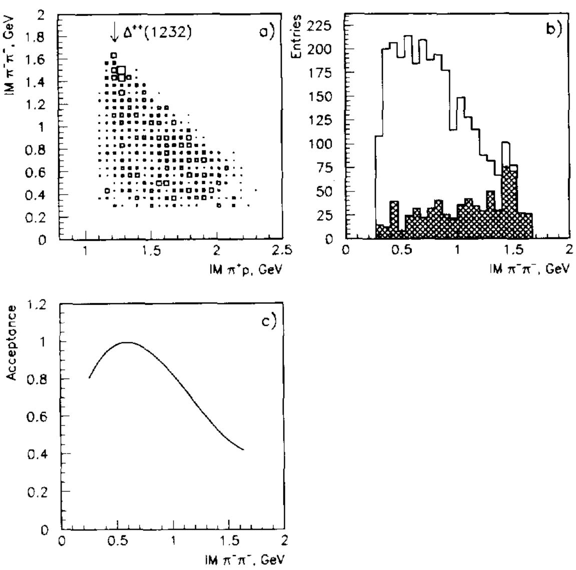

Fig. 5. (a) Scatter plot for invariant mass of the $\pi^-\pi^-$ system versus invariant mass of π^+p system for the reaction (1). (b) The scatter plot projection to the vertical axis. The hatched histogram corresponds to the events with the invariant mass of the π^+p system satisfying the following condition: $|M_{\pi^+p} - M_{\Delta^{++}}| \leq 120$ MeV. (c) Apparatus acceptance for the events shown in figure (b) by the hatched histogram.

ant mass of the π^+p system satisfying the following condition: $|M_{\pi^+p} - M_{\Delta^{++}}| \leq 120$ MeV (in Fig. 5(c) the apparatus acceptance for these events is shown). As one can see, there is a small bump in the high mass part of the $\pi^-\pi^-$ invariant mass distribution, but this bump has a small statistical significance, so we can perform only an upper limit estimation on reaction (7). To do this the distribution in Fig. 5(b) was approximated at a first stage by a second-order polynomial function. The parameters of this polynomial function were fixed and the experimental invariant mass distribution of the $\pi^-\pi^-$ system was fitted at the second stage by the function:

$$F = A_1 \times BW(\Gamma_{\pi^-\pi^-}, M_{\pi^-\pi^-}, m) + A_2 \times \sum_{i=1,\dots,3} b_i \times m^{i-1} ,$$

where $BW(\Gamma_{\pi^-\pi^-}, M_{\pi^-\pi^-}, m)$ is the Breit-Wigner function (6). During the fit, the parameters A_1, A_2, $M_{\pi^-\pi^-}$ were free, the parameters of the polynomial function were fixed from the first stage of approximation and the $\Gamma_{\pi^-\pi^-}$ parameter was fixed at a value of 60 MeV according to the theoretical prediction. Using the results of this fit, the upper limit on reaction (7) was estimated to be:

$$Y_{\bar{p}\,(\Delta^-\Delta^{++})\to 2\pi^-\pi^+p} \leq 6.5 \times 10^{-5} \qquad (8)$$

with a 90% confidence level.

Finally, let us suppose that the branching ratio of the reaction $\bar{p}\,\Delta^- \to 2\pi^-$ is approximately the same as for $\bar{p}N \to 2\pi$, that is $\approx 5 \times 10^{-3}$ [29]. Using this assumption and the upper limit (8) we can roughly estimate the probability to find the deuteron as the $\Delta\Delta$ configuration. This probability is $P_{\Delta\Delta} \leq 1\%$, a value of the same order of magnitude as the upper limit obtained in other experiments reported above and in agreement with the theoretical predictions.

4. Summary and conclusions

We have presented the results of a study of antiproton annihilation at rest in deuterium gas performed with the OBELIX detector at LEAR (CERN).

We studied $\bar{p}d$-annihilation into three and five charged pions with a high proton momentum in the final state. The annihilation probabilities via channels (2) and (4) with proton momenta $p > 400$ MeV/c in the final state have been measured for the first time :
$Y_{\bar{p}d \to 2\pi^-\pi^+\pi^0p} = (93.2 \pm 1.6 - 14.9) \times 10^{-4}$,
$Y_{\bar{p}d \to 3\pi^-2\pi^+\pi^0p} = (52.2 \pm 1.5 - 0.1) \times 10^{-4}$.
The $\bar{p}d$ annihilation probabilities via channels (1) and (3):
$Y_{\bar{p}d \to 2\pi^-\pi^+p} = (15.3 \pm 0.4 - 1.5) \times 10^{-4}$ and
$Y_{\bar{p}d \to 3\pi^-2\pi^+p} = (37.9 \pm 1.0 - 0.4) \times 10^{-4}$
are in good agreement with our previous measurements [5].

The signal from the Δ^{++}-isobar was clearly seen in all analysed reactions. The total number of Δ^{++}-isobars was found to be (183 ± 27), (1621 ± 188), (1772 ± 120) and (1589 ± 163) events in the channels (1)-(4), respectively. The fraction of events with the Δ^{++}-isobar increased with the pion multiplicity in the final state and reached 55% for the reaction $\bar{p}d \to 3\pi^-2\pi^+\pi^0p$.

The upper limit on reaction (7) in the $p\bar{d}$ annihilation at rest was found to be :

$$Y_{\bar{p}\,(\Delta^-\Delta^{++})\to 2\pi^-\pi^+p} \leq 6.5 \times 10^{-5}$$

with a 90% confidence level. This figure gives us a rough estimate of the probability to find deuteron as the $\Delta\Delta$-configuration $P_{\Delta\Delta} \leq 1\%$ and this value is of the same order of magnitude as the data obtained earlier in other experiments.

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