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Light baryon production in binary $\bar{p}d$ annihilation reactions at rest

OBELIX Collaboration

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Abstract

We report the study of light baryon production in two-prong annihilation reactions due to antiprotons stopping in gaseous deuterium and detected by the OBELIX spectrometer (LEAR, CERN). A clear signal of the $\Delta(1232)$ production in binary reactions was found in both annihilation channels: $\bar{p}d \to \pi^- \Delta^+ (\Delta^+ \to \pi^0 p)$ and $\bar{p}d \to \pi^0 \Delta^0 (\Delta^0 \to \pi^- p)$. The annihilation probabilities for these reactions turned out to be $Y = (1.01 \pm 0.08) \times 10^{-5}$ and $Y = (1.12 \pm 0.20) \times 10^{-5}$, respectively. In addition, the annihilation probability for the prototype Pontecorvo reaction $\bar{p}d \to \pi^- p$ was measured with the best world statistics: $Y = (1.46 \pm 0.08) \times 10^{-5}$. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

Since its discovery the $\Delta(1232)$-isobar played a central role not only for its dominant contribution in the πN interaction at intermediate energies but also as a possible constituent in the description of NN binding in nuclei.

Recently, Δ production following $\bar{p}$ annihilation at rest on deuterium nuclei has been identified by the OBELIX Collaboration [1,2] in reactions with 3 to 6 pions in the final state. The features of this production should apparently be ascribed to a ''conventional'' on shell pion rescattering on the spectator nucleon. Indeed, $\bar{p}d$ annihilation at rest represents a rich source of pions with energies close to the excitation energy of the Δ resonance, pions that are produced either directly at the annihilation vertex or through the decay of heavier mesons.

The Δ-isobar has been observed, also, in the final state of the Pontecorvo binary reactions induced by $\bar{p}$ annihilation at rest in deuterium.

The Pontecorvo reactions, characterized by only one meson in the final state, cannot be ascribed to the usual annihilation dynamics which produces at least two mesons in the final state together with the spectator nucleon. Annihilation mechanisms, based on quark degrees of freedom of the nuclei have been envisaged for this class of reactions [3]. Models based on absorptive rescattering of off-shell mesons, produced at the annihilation vertex, have been widely explored [4–6].

The Crystal Barrel Collaboration at LEAR(CERN) [7,8] and Chiba et al. at KEK [9] have measured, besides the prototype Pontecorvo reaction $\bar{p}d \to \pi^0 n$, the channel $\bar{p}d \to \pi^0 \Delta^0 (\Delta^0 \to \pi^0 n)$. Both experiments were optimized for γ detection and measurement. The results of these measurements are consistent within two standard deviations, exibitin uncertainties as large as 10% and 35%, respectively.

In this paper we present the results of an analysis of a two-prong data sample collected by the OBELIX spectrometer at the LEAR facility of CERN.

We present in the following a new measurement of the branching ratio of $\bar{p}d \to \pi^0 \Delta^0$ through the charged decay channel $\Delta^0 \to \pi^- p$ and the first measurement of the isospin conjugate channel $\bar{p}d \to \pi^- \Delta^+ (\Delta^+ \to \pi^0 p)$. So, a full set of measurements is available for comparison with the predictions of the theoretical models.

Moreover, to check the reliability of these new results, we repeated the measurement of the prototype Pontecorvo reaction $\bar{p}d \to \pi^- p$.

All the Pontecorvo reactions described above are characterized by a fast nucleon in the final state and the OBELIX spectrometer has unique features in order to separate protons from pions and kaons with a very high confidence level for a wide range of particle momenta.

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2. Experimental apparatus, trigger and event selection

The OBELIX spectrometer is a close to 4π geometry detector designed for registration of both charged and neutral products of antiproton annihilation in targets with different densities [10,11]. The spectrometer consists of five main parts (starting from the beam line toward the periphery):

- a cylindrical target (gas at NTP, low pressured gas, liquid);
- a Spiral Projection Chamber, the vertex detector of OBELIX;
- two barrels of the Time-of-Flight system which serves for π, K and p separation in the final state and as the main trigger device;
- a Jet Drift Chamber, the main tracking device of OBELIX, used also for charged particle identification by dE/dX;
- a High Angular Resolution Gamma Detector, the electromagnetic calorimeter for γ detection.

Only information from the TOF system and JDC was used in the data analysis described below.

The data sample collected during the November 1995 run was used for the analysis presented in this paper. The conditions of the run were the following:

- antiproton annihilation at rest;
- deuterium gas target at Normal Temperature and Pressure.
- trigger conditions suitable for any two prong events:
  - two hits in the internal TOF barrel;
  - two hits in the external TOF barrel;
  - correlation between internal and external TOF slabs for selection of long tracks.

An overall statistics of 8.6×10^6 events with a multiplicity trigger was collected. A control sample of 2.5×10^6 minimum bias events was also collected. The minimum bias events were registered under the minimal trigger condition of $\bar{p}$ annihilation within the target region and with a flag when the pattern required by the multiplicity trigger was recognized.

The following selection criteria were applied to the events:

- number of tracks in the JDC equal to 2;
- total charge of the particles in the final state equal to 0;
- track length in the JDC $L_{\mathrm{TR\,JDC}} \geq 25\,\mathrm{cm}$;
- positively charged particle recognized as a proton by both TOF and dE/dX (JDC) particle identification systems (see Fig. 1);
- momentum of the proton in the final state higher than $400\,\mathrm{MeV/c}$ to exclude the low acceptance region, where protons undergo significant energy loss in the matter distributed between the target and the outer barrel of the TOF system.

The total number of events that survived these cuts was $\approx 1.1 \times 10^5$.

3. Data analysis

3.1. $\bar{p}d \to \pi^- p$

The Pontecorvo prototype reaction $\bar{p}d \to \pi^- p$ together with its isospin conjugate $\pi^0 n$ have been

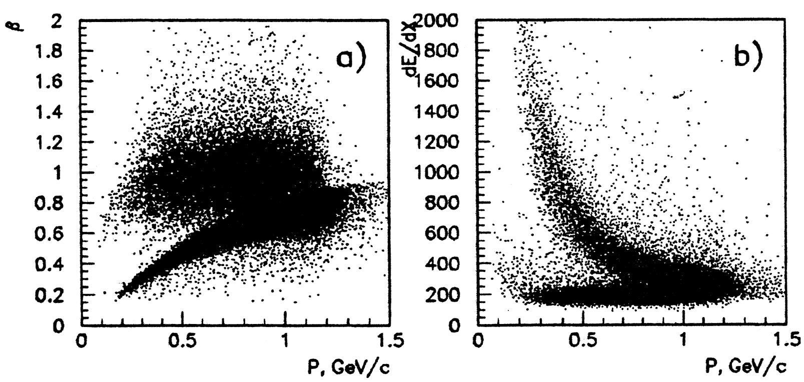

Fig. 1. β (a) and dE/dX (b) versus momentum of the particle (two prong events).

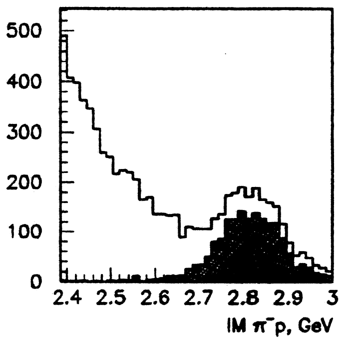

Fig. 2. Invariant mass of the $\pi^- p$ system.

measured repeatedly [13,1,7,9]; $\pi^- p$ is the channel measured with the best statistics. We measured the branching ratio of this reaction for our sample of events, with the aim of testing the reliability of our data analysis. To identify the reaction $\bar{p}d \to \pi^- p$ a 4C kinematical fit was applied. Events fitting the hypothesis at a 90% C.L. were retained. The invariant mass distribution of the $\pi^- p$ system for the accepted events is presented in Fig. 2 (hatched area) together with the corresponding distribution for all the two-prong events submitted to the kinematical fit (solid line). For the selected events, the invariant mass distribution is fairly symmetric (skewness parameter 5×10^{-2}) and centered around the $\bar{p}d$ mass. As a consequence the contamination induced by the background $\pi^- \pi^0 p$ final state can be neglected.

The total number of events of the reaction $\bar{p}d \to \pi^- p$ was found to be $N_{\pi^- p} = 1731$. This is the best world statistics for this reaction channel, and we will reconsider it below in the ''results discussion'' section.

3.2. $\bar{p}d \to \Delta\pi$ channels

In order to select the $\bar{p}d \to \Delta\pi$ reaction, we consider the proton momentum distribution in Fig. 3a for all the selected two prong events.

Two shoulders can be observed in this distribution in the regions of 800 MeV/c and 900 MeV/c, respectively. The origin of these shoulders is a contamination of misidentified pions and kaons, coming from the binary annihilation reactions with an unobserved proton spectator in the final state $\bar{p}d \to \pi^- \pi^+ p_s$ and $\bar{p}d \to K^- K^+ p_s$. We have no possibility to separate reliably protons from other particles in this momentum region. The contribution of the $\pi\Delta$ channel is expected to be important in the region above 700 MeV/c with a maximum at 1 GeV/c, as it can be deduced from Fig. 3b, where the proton momentum distribution for the Monte Carlo simulated reaction $\bar{p}d \to \Delta\pi$ is shown. So, to reduce the background we retained for further analysis only the events with proton momenta in the final state $P_{prot} \geq$ 600 MeV/c.

Since π^0 were not measured, to select $\bar{p}d \to \pi^- \pi^0 p$ reactions among the two prong ones, the

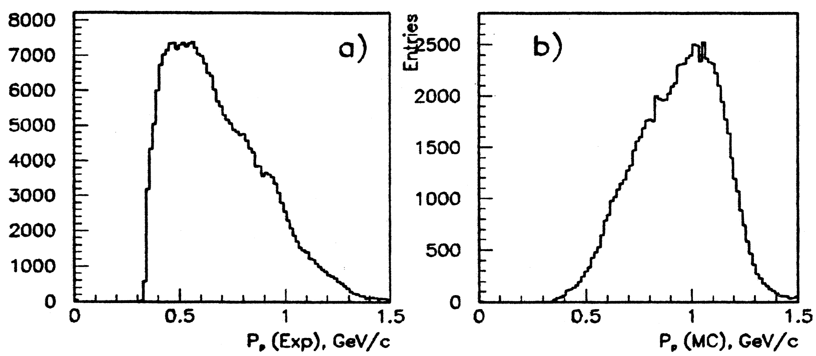

Fig. 3. (a) inclusive proton momentum distribution for two prong events; (b) simulated proton momentum distribution for the binary annihilation channel $\bar{p}d \to \Delta\pi$.

events were filtered by a 1C kinematical fit. The selected events include the reactions

$$\bar{p}d \rightarrow \pi^- \pi^0 p \tag{1}$$

$$\bar{p}d \rightarrow \Delta^+ \pi^- \qquad \Delta^+ \rightarrow \pi^0 p \tag{2}$$

$$\bar{p}d \rightarrow \Delta^0 \pi^0 \qquad \Delta^0 \rightarrow \pi^- p \tag{3}$$

where (1) is contributed by $(\bar{p}n)p_s \rightarrow \pi^- \pi^0 p_s$, $\bar{p}d \rightarrow \rho^- p$ and uncorrelated $\pi^- \pi^0 p$. Reaction (1) must be considered a background for the other two. To select (2) and (3), a proper cut on the $\pi^- \pi^0$ invariant mass was introduced on the basis of MonteCarlo simulations. Since all the above reactions can be followed by a final state interaction we did not introduce any specific angular distribution for Monte Carlo events and all the decays were simulated according to available phase space. The corresponding distributions of the invariant mass of the $\pi^0 p$ system versus the invariant mass of the $\pi^- \pi^0$ for the simulated events are shown in Fig. 4a for channel (3) and in Fig. 4b for channel (1). According to Fig. 4b, most of background is excluded from Fig. 4c when events with $M_{\pi^- \pi^0} \leq 1.5\,\mathrm{GeV}$ are rejected. Obviously, in the case of channel (2) the Monte Carlo scatter plot of the $\pi^- p$ system invariant mass versus the $\pi^- \pi^0$ system invariant mass is quite similar to the corresponding plot for channel (3).

For events surviving these cuts the invariant mass distributions of the $\pi^- p$ (Fig. 5a,c) and $\pi^0 p$ (Fig. 5b,d) systems were analysed. As one can see, there are several peaks in these invariant mass distribu-

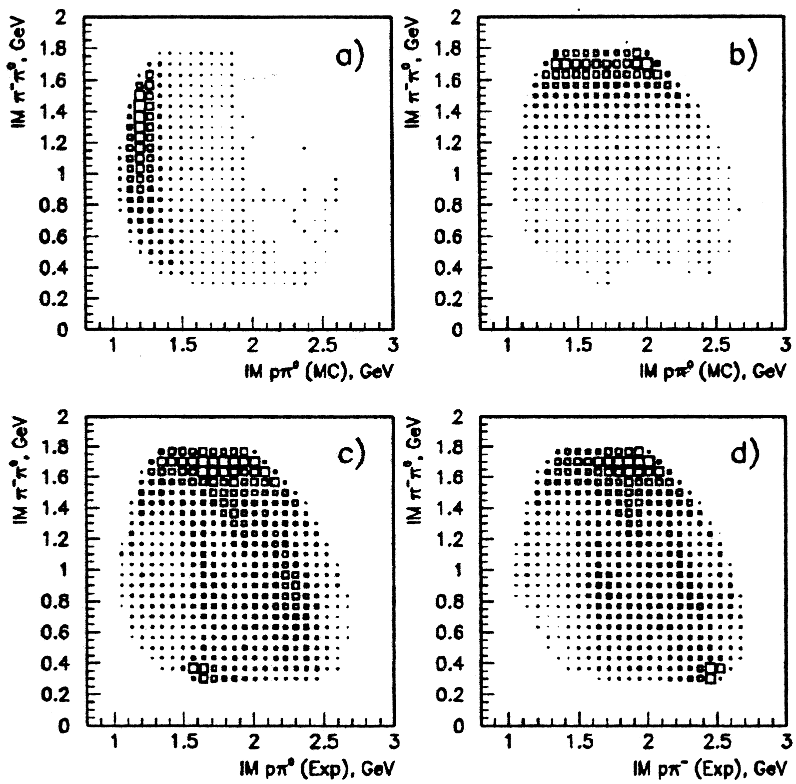

Fig. 4. Scatter plots of the $\pi^- \pi^0$ system invariant mass versus the πp system invariant mass (a) for simulated events of the reaction $\bar{p}d \rightarrow \pi^0 \Delta^0$, (b) for simulated events of the reaction $\bar{p}d \rightarrow \pi^0 \pi^- p$, (c,d) for the experimental data.

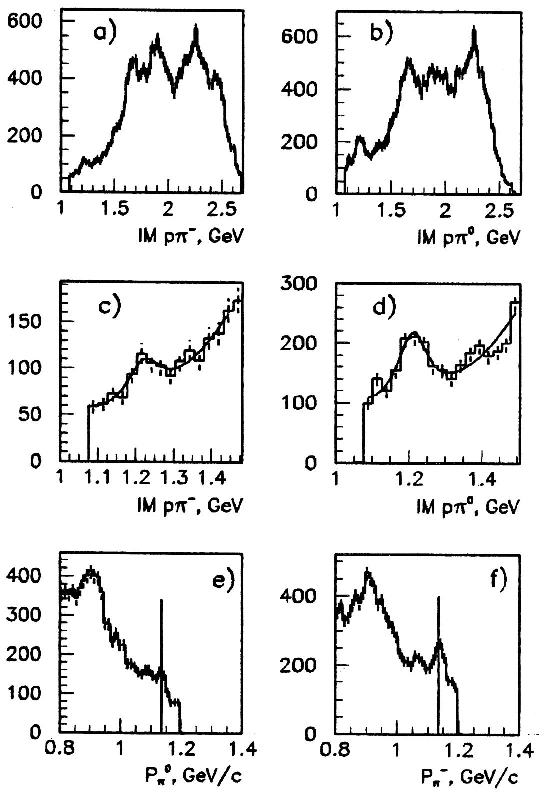

Fig. 5. (a,c) invariant mass distribution of the $\pi^- p$ system, (b,d) invariant mass distribution of the $\pi^0 p$ system, (e,f) π^0 and π^- momentum distribution for channel $\bar{p}d \to \pi^0 \pi^- p$. Figs. c) and d) show details of a) and b), respectively.

tions, besides $\Delta(1232)$), that correspond to invariant masses of the πp system equal to $\approx$ 1650 MeV,1750 MeV, 2250 MeV, etc.

A number of well known baryonic states may contribute to these peaks: $\Delta(1620)$, $N(1650)$, $\Delta(1700)$, $N(1720)$ and others reported by PDG. The lack of statistics does not allow performing a partial wave analysis of these spectra and determining the exact parameters of these resonances and their relative contributions. Qualitatively, a more clear signal is observed for the relatively heavier isobar states, whereas the well known πp rescattering data show an opposite behaviour. This experimental feature may be explained within the two-step approach to the Pontecorvo reactions.

Indeed, it was observed [12] that, generally, in reactions like $\bar{p}d \to NM$ where $N = n, p$ and M is a meson, the production of the light mesons is reduced as compared to the heavy mesons. This peculiar behaviour is related to the dependence of the deuteron form factor on the invariant momentum transfer t and on the dependence of t on the mesonic mass. t decreases as the meson mass decreases (see Fig. 6). A small mesonic mass implies high momenta of the meson and of the recoiling nucleon. But a nucleon in the deuteron has a low probability to have a high momentum, i.e. a small $p - n$ distance. Similarly, if the class of reactions $\bar{p}d \to \pi B$ is considered, where B is a baryon like N, Δ or N^*, then t exibits the behaviour shown in Fig. 6, and the probability to emit a baryon is expected to increase with the baryon mass.

A similar feature was observed in $\bar{N}N$ where the two-body decay modes, assumed to be the dominant ones, cannot be quantitatively described on the basis of the available phase space, which should enhance the production of light mesons. A decay picture with a bias in favour of high masses was introduced [16]. The model is inspired by the idea that the $\bar{N}N$ system, a factory of mesons, could itself have me-

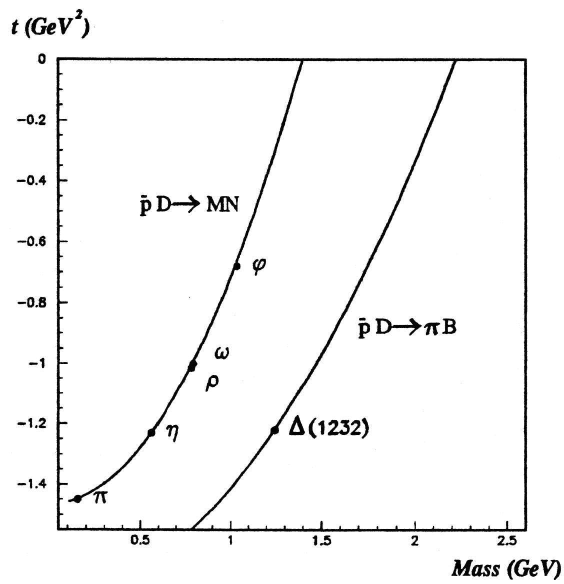

Fig. 6. Dependence on the mass of the meson M recoiling against a nucleon in the reaction $\bar{p}d \to MN$ and on the mass of the baryon B recoiling against the pion in the reaction $\bar{p}d \to \pi B$. Arrows correspond to the reactions $\bar{p}d \to \pi N$ and $\bar{p}d \to \pi\Delta$.

Table 1
Results of the different experiments on prototype Pontecorvo reaction $\bar{p}d \to \pi^- p$ measurements (*: the annihilation channel $\bar{p}d \to \pi^0 n$ was measured)

N_{events}	$Y, 10^{-5}$	Experiment
6	0.9 ± 0.4	Bubble cham. [13]
5	1.4 ± 0.7	Asterix [14]
	$1.03 \pm 0.4^*$	KEK [9]
542	1.29 ± 0.13	Obelix [15]
677	$0.703 \pm 0.072^*$	Crystal Barrel [7]
1731	1.46 ± 0.08	Obelix (this paper)

son-like dynamical properties. To describe the observed effects, the usual phase space prediction is corrected by a factor containing the nearest threshold dominance [17], which favours the production of heavy resonances over lighter ones.

In this paper we study only the $\Delta(1232)$-isobar production in the binary reaction. To extract the $\Delta(1232)$ signal the πp invariant mass distributions were fitted by the function:

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

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

$$\mathrm{BW}(\Gamma_\Delta, M_\Delta, m) = \frac{\Gamma_\Delta}{\left((m - M_\Delta)^2 + (\Gamma_\Delta/2)^2\right)}$$

All parameters, except the width of the Δ set to 120 MeV, were free during the fit of the distribution shown in Fig. 5c. The fit yields the following parameters of the isobar:

- $M_{\Delta \to \pi^- p} = (1222 \pm 11)$ MeV and
- $\Gamma_{\Delta \to \pi^- p} = 120$ MeV (fixed),
- $M_{\Delta \to \pi^0 p} = (1211 \pm 8)$ MeV and
- $\Gamma_{\Delta \to \pi^0 p} = (106 \pm 20)$ MeV.

If the Δ-isobar is really produced in a binary reaction, the pion momentum distribution must show a peak at ≈ 1.130 GeV/c, the value predicted by the two-body $\pi\Delta$ reaction kinematics. These peaks are displayed by the π^- and π^0 momentum distributions of Fig. 5e and Fig. 5f. It should be noted that these peaks are a direct consequence of the final state selection by the kinematical fit and do not represent an independent proof of the existence of the corresponding annihilation channel.

In conclusion, we can state that for the first time clear signatures of both the possible Pontecorvo reactions with the Δ-isobar in the annihilation channel and with two charged particles in the final state have been detected. The number of events of reactions (2) and (3) were found to be $N_{\pi^0\Delta^0} = 354 \pm 74$ and $N_{\pi^-\Delta^+} = 770 \pm 61$.

4. Discussion of the results

As we have already noted, the Pontecorvo reactions have been studied by a number of experimental groups in spite of the fact that there are intrinsic experimental difficulties in distinguishing the signal from the background, due to the low value of the branching ratios. The difficulties are greater in the case of Pontecorvo reactions with broad resonances in the final state. In this section we evaluate the annihilation probability or yields (Y) for the prototype Pontecorvo reaction $\bar{p}d \to \pi^- p$ and for the reactions (2) and (3), and we compare our results with those of other experiments. We calculate the yields from the formula $Y = N_{eV}/(\varepsilon_{MC} \times N_{ann})$. Here N_{eV} is the number of events of the corresponding reaction, ε_{MC} is the registration efficiency which includes the geometrical acceptance, the trigger efficiency, the detector efficiencies, and a correction for the annihilation into all neutrals; N_{ann} is the total number of annihilations ($8.2 \times 10^8 \bar{p}$/target). Our result for the prototype Pontecorvo reaction is compared to previous results in Table 1.

The new Obelix data agree with the previous measurements, but the present statistics is much higher then previously. Our results in reactions (2) and (3) are given in Table (2) and compared to the previous measurements in Table (3). We note that, because of the isospin invariance, the annihilation probability of the channel $\bar{p}d \to \pi^0 n$ is connected

Table 2
Results of the Obelix experiments on Pontecorvo reactions $\bar{p}d \to \pi^0\Delta^0$ and $\bar{p}d \to \pi^-\Delta^+$

N_{events}	$Y, \times 10^{-5}$	Final state
354	1.22 ± 0.20	$\pi^0\Delta^0(\pi^- p)$
770	1.01 ± 0.10	$\pi^-\Delta^+(\pi^0 p)$

Table 3
Results of the different experiments on Pontecorvo reaction $\bar{p}d \to \pi^0\Delta^0$ (* - recalculated under the isospin invariance)

N_{events}	$Y, \times 10^{-5}$	Experiment
	4.67 ± 1.66	KEK [9]
657	2.21 ± 0.24	Crystal Barrel [8]
770	$2.0 \pm 0.2^*$	Obelix (this paper)
354	2.4 ± 0.4	Obelix (this paper)

with the prototype reaction according to the ratio $Y_{\pi^0 n} = \frac{1}{2} Y_{\pi^- p}$.

As it was already discussed before, only two independent measurements of the Pontecorvo reaction have been performed till now with the Δ-isobar in the final state: one by the Crystal Barrel Collaboration, and another by the KEK group. They studied the same final state

$$\begin{aligned} \bar{p}d \quad \to \quad & \Delta^0\pi^0 \\ & \Delta^0 \to \pi^0 n \end{aligned} \tag{4}$$

but applied different approaches to the signal selection. Crystal Barrel analysed the final state invariant mass and angular distributions in the exclusive final state $\bar{p}d \to \pi^0\pi^0 n$ and the KEK group only analysed the momentum spectrum of the recoiling π^0-meson in the inclusive annihilation channel $\bar{p}d \to \pi^0 X$.

So, in both experiments the $\pi^0\Delta^0$ final state was measured through neutral particles, while we measured charged particles. Our values for the two yields coincide within errors, as expected according to the isospin invariance $Y_{\pi^-\Delta^+(\pi^0 p)} = Y_{\pi^0\Delta^0(\pi^- p)}$. This stresses the selfconsistence of our measurements.

To compare our results with the previous ones we recall that, according to the isospin invariance, the equality

$$Y_{\pi^0\Delta^0(\pi^0 n)} = 2Y_{\pi^0\Delta^0(\pi^- p)} = 2Y_{\pi^-\Delta^+(\pi^0 p)} \tag{5}$$

holds. So we introduce into Table 3 the values of Table 2 multiplied by the factor 2. One can see that our values are perfectly consistent with the one obtained by Crystal Barrel. As far as the KEK value is concerned, it is higher than ours, but its error is quite large.

5. Conclusions

The yields for the Pontecorvo reactions

$$\begin{aligned} \bar{p}d \quad \to \quad & \Delta^+\pi^- \\ & \Delta^+ \to \pi^0 p \end{aligned} \tag{6}$$

$$\begin{aligned} \bar{p}d \quad \to \quad & \Delta^0\pi^0 \\ & \Delta^0 \to \pi^- p \end{aligned} \tag{7}$$

have been measured for the first time. The measured yields are equal within errors taking into account to the isospin invariance and are consistent with the yield of the reaction

$$\begin{aligned} \bar{p}d \quad \to \quad & \Delta^0\pi^0 \\ & \Delta^0 \to \pi^0 n \end{aligned} \tag{8}$$

measured in previous experiments.

As a test of the reliability of the above measurements, the yield of the prototype Pontecorvo reaction

$$\bar{p}d \to \pi^- p$$

has also been measured with a statistics much higher than in previous measurements. The new value is in good agreement with the old ones.

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