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PONTECORVO REACTIONS AS A GENERAL CLASS OF ANTIPROTON ANNIHILATION ON NUCLEI

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Реакции Понтекорво как общий класс
процессов антипротон-ядерной аннигиляции

Рассматриваются реакции аннигиляции антипротонов, запрещенные на свободном нуклоне, но которые могут происходить на связанном нуклоне. Показано, что изучение таких процессов может быть существенным для выяснения роли ненуклонных степеней свободы в ядре. Эти реакции хороши также для поиска экзотических состояний.

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Kharzeev D.E., Nichitiu F., Sapozhnikov M.G. E2-92-64
Pontecorvo Reactions as a General Class
of Antiproton Annihilation on Nuclei

Reactions of antiproton annihilation forbidden on a free nucleon but allowed on a bound one are considered. It is shown that the investigation of these reactions can be essential in clarifying the role of non-nucleonic degrees of freedom in nuclei. It can be also a good tool for search for exotic resonances.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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B.Pontecorvo was the first who as early as 1956 drew attention [1] to the possibility of unusual annihilation processes forbidden on a free nucleon but allowed on a bound nucleon. In ordinary annihilation of an antiproton with a nucleon at least two mesons should be created. However, if annihilation takes place in a nucleus, it is possible to create only one meson in the final state, for instance

$$\bar{p} + d \Rightarrow \pi^- + p \tag{1}$$

$$\bar{p} + d \Rightarrow \pi^0 + n \tag{2}$$

$$\Rightarrow \eta + n$$

$$\bar{p} + d \Rightarrow K^+ + \Sigma^- \tag{3}$$

or to arrange the annihilation without any mesons, for example:

$$\bar{p} + {}^3He \Rightarrow p + n \tag{4}$$

$$\bar{n} + {}^3He \Rightarrow p + p\,. \tag{5}$$

Unfortunately, the experimental information about the Pontecorvo reactions is rather scarce. The reaction (1) has been observed [2-4] in antiproton annihilation at rest with the branching ratio $W(\pi^- p)$ at the level of 10^{-5}. New precise measurements of this reaction were made by the OBELIX collaboration [5]. The reactions (2) were seen recently by the Crystal Barrel collaboration [6]. An upper limit was imposed [3] on the relative probability of reaction (3) for stopped antiprotons: $W(K^+\Sigma^-) < 8\times10^{-6}$. The mesonless annihilation processes (4)-(5) have not been investigated up to now.

In the conventional approach one may treat the reactions (1)-(3) as two-step processes shown in Fig.1.

After antiproton annihilation on a bound nucleon two mesons are created and one of them is absorbed on the second nucleon of the deuteron. Clearly, this process of the meson absorption on one nucleon is characterized by rather high momentum transfer. Thus the amplitude of the process must be very sensitive to small internucleon distances in the deuteron.

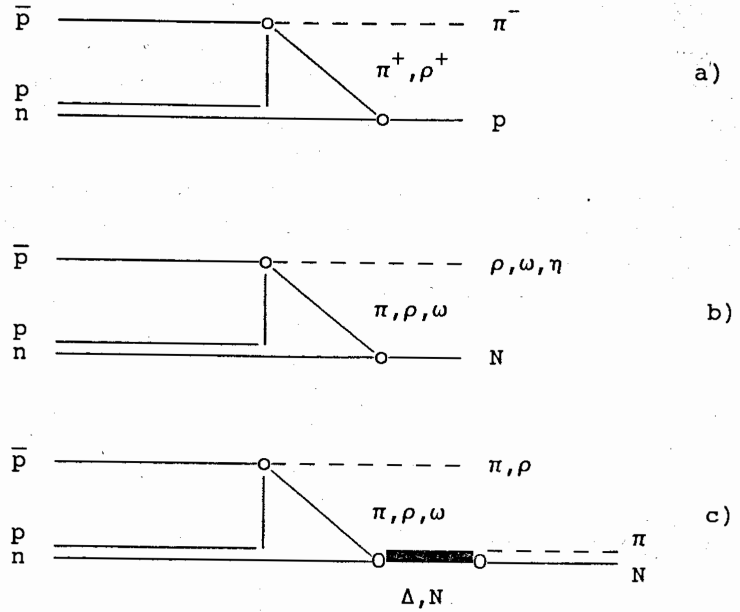

Fig.1 - Diagrams for the Pontecorvo reactions $\bar{p} + d \Rightarrow M + N$.

This conclusion is confirmed by the results of concrete calculations of reactions (1)-(4) performed in [7-9]. The probability of Pontecorvo reactions was found to be strongly dependent on the choice of the deuteron wave function. Nevertheless, it seems that the two-step model predicts [7] a too small branching ratio for the reaction (1) (at the level of few units times 10^{-6}). An impression about an agreement between the experimental data and theoretical models can be obtained from Table 1, in which some typical predictions are presented.

Table 1. The branching ratios of different Pontecorvo reactions for $\bar{p}p$ annihilation at rest. Comparison between theory and experiment.

THEORY	[7]	[8]	[10]	[9]	[13]
$\bar{p} + d \Rightarrow \pi^- + p$	$2.7\ 10^{-6}$	$3.8\ 10^{-5}$	$3.0\ 10^{-5}$	$8.5\ 10^{-6}$	
$\Rightarrow K^0 + \Lambda$	$3.1\ 10^{-7}$		$8.1\ 10^{-6}$		
$\Rightarrow K^+ + \Sigma^-$	$7.6\ 10^{-9}$	$2.5\ 10^{-8}$	$7.8\ 10^{-6}$		
$\bar{p} + {}^3He \Rightarrow p + n$					$(7.7\text{-}13.4)\ 10^{-9}$

EXPERIMENT:		
	$W(\bar{p}\ d \Rightarrow \pi^- p) = (0.9 \pm 0.6)\ 10^{-5}$	[2]
	$= (2.8 \pm 0.3)\ 10^{-5}$	[3]
	$= (1.4 \pm 0.7)\ 10^{-5}$	[4]
	$= (9.6 \pm 1.7)\ 10^{-6}$	[5]
	$W(\bar{p}\ d \Rightarrow K^+\Sigma^-) < 8\ 10^{-6}$	[3]

Alternative approaches were considered in [10-13]. Thus in [10] the yields of reactions (1),(3) are calculated within the model of evaporation of a fireball with B=1 baryon charge. To obtain the experimental yield of the reaction (1) an assumption is needed that the fireballs are formed in 10% of all $\bar{p}A$ annihilations.For the probabilities of reactions (3) this model predicts the values at the level of 10^{-6}, just slightly below the existing experimental limit. These results sharply contrast with the predictions of two-step models which give $W(K^+\Sigma^-) \approx 10^{-8}$ [7,8].

In another approach, investigated in [11,12], the Pontecorvo reactions are treated using information from line-reversed reactions using a "quasi-detailed balance" method [12] or in a more elaborate way on the basis of the reggeon diagram technique [11]. The author of [11] predicts probabilities for (1),(3) which lie somewhere between the extreme predictions of [10] and those of the two-step models.

In principle, one may try to treat Pontecorvo reactions in terms of quarks as a process, where antiquarks of the antiproton annihilate on quarks of both nucleons (see, for instance, diagram in Fig.2).

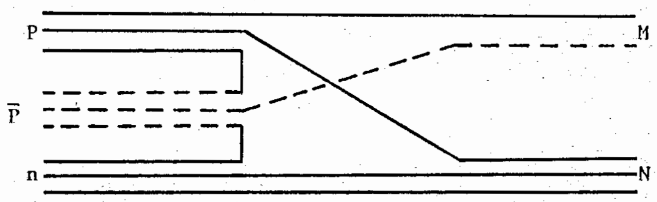

Fig.2 Antiproton annihilation on two nucleons.

The admixtures of multiquark states in the deuteron wave function have been introduced in [13]. For 0.3% admixture of a 6-q bag the predicted branching ratio for the reaction (1) coincides with the experimental value.

It is important to note that the definition of the Pontecorvo reactions as processes which are forbidden in the annihilation on the free nucleon but allowed on the bound one is rather broad and a lot of processes are covered by this definition. For instance, there should exist a lot of one-meson annihilation reactions like

$$\bar{p} + d \Rightarrow M + N , \qquad (6)$$

where M stands for any heavy meson, like η,ρ,ω ...etc. (see the diagram of Fig.1b)

The class of the Pontecorvo reactions also includes the processes of the resonance formation

$$\bar{p} + d \Rightarrow M + N^{*} , \qquad (7)$$

where N^{*} may be any baryon resonance, like Δ(1232) or N(1540). (see, the diagram of Fig.1c).

It is instructive to analyze the characteristics of (6)-(7) plotting the dependence of the invariant momentum transfer t versus the mass M_{eff} of the produced mesonic system (see Fig.3).

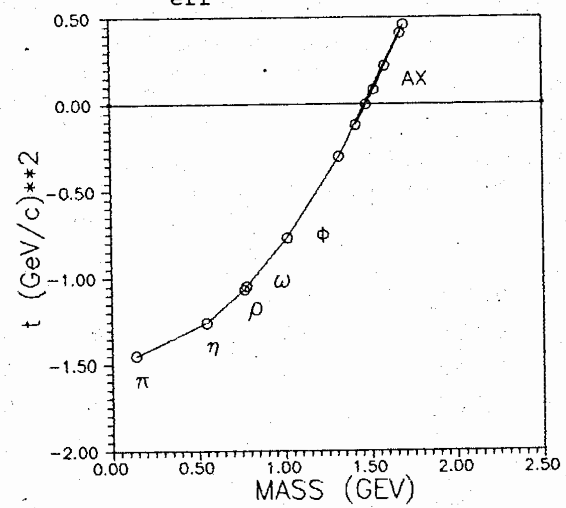

Fig.3 Dependence of the invariant momentum transfer t on the mass M_{eff} of mesonic system in the Pontecorvo reactions $\bar{p} + d \Rightarrow M + N$.

One can see that for a reaction with light meson production, the t is negative and reaches t=-1.5 GeV^2 for the case of pion. When the mass of the mesonic system M_{eff} increases to the value of $M_{eff} \approx 2m_N$, the momentum transfer tends to the value of $t=m^2_N$ corresponding to the annihilation on a free nucleon. It is clear that in the vicinity of $t=m^2_N$ the leading diagram will be the one with the nucleon pole. Bearing in mind strong dependence of the deuteron form factor on t one could understand that, in general, the production of light mesons will be suppressed with respect to the heavy ones.

Let us compare the characteristics of (6)-(7) with those for the "conventional" Pontecorvo reaction $\bar{p}d \Rightarrow \pi^- p$. In Table 2 the average momenta of the final state particles produced in some reactions (6)-(7) of $\bar{p}d$ annihilation at rest are given. If these processes proceed via the two-step mechanism, their branching ratios should depend upon the probability of the first step, i.e. on the probability of the $\bar{p}p$ annihilation into two mesons. Some of the relevant two meson branching ratios are given in the Table 2.

Table 2. The characteristics of the Pontecorvo reactions (6)-(7). T_M and T_N stand for kinetic energies of the meson and the nucleon in the final state, P is their averaged momentum calculated for the nominal resonance mass and for annihilation at rest. $W(\bar{p}p\text{--}M_1M_2)$ is the branching ratio of $\bar{p}p$ annihilation into two mesons on the first step [14].

Final state	Intermediate state	$W(\bar{p}p\text{--}M_1M_2)$ %	P GeV/c	T_M GeV	T_N GeV
π^- p	$\pi^+\pi^-$	0.37± 0.3	1.246	1.114	0.621
ρ^- p	$\pi^+\rho^-$	1.5 ± 0.3	1.116	0.586	0.520
ω n	$\pi^0\omega$	0.52± 0.05	1.111	0.576	0.515
$a_0^-(980)$ p	$\pi^+a_0^-$	0.38± 0.06	1.029	0.441	0.454
$f_2(1270)$ n	$\pi^0 f_2$	0.24± 0.07	0.865	0.267	0.338
$a_2(1320)^-$p	π^+a_2	1.32± 0.10	0.832	0.240	0.316
AX(1560) n	π^0AX	0.37± 0.06	0.630	0.122	0.192
π Δ(1232)	π π	0.37± 0.3	1.130	1.00	0.441

Inspection of this Table immediately reveals that the nucleon from Pontecorvo reactions (6) should have a significant momentum, greater than 1 GeV/c in the case of ρN or ωN final states. Even for annihilation into a heavy meson, like AX(1560) [15], the momentum of associated nucleon is 0.630 GeV/c.

From the results presented in Table 2 one may see again, that the simplest Pontecorvo reaction $\bar{p} + d \Rightarrow \pi^- + p$ is by no means the most probable. In fact, the probability to see the channels like

$$\bar{p} + d \Rightarrow \rho^- + p \qquad (8)$$

or

$$\bar{p} + d \Rightarrow a_2^- + p \qquad (9)$$

seems to be more favourable owing to higher branching ratios in $\bar{p}N$ annihilation.

First estimations of the probabilities of the Pontecorvo reactions with different mesons M were done in [16]. It was predicted that the branching ratio of the reaction $\bar{p} + d \Rightarrow \rho^- + p$ may be two times greater than that of $\bar{p} + d \Rightarrow \pi^- + p$ and the branching ratio of (9) may be even greater, at the level of 10^{-4}.

In general, one should regard as a Pontecorvo reaction all processes like (6) or (7) which cannot take place on free nucleon or be a consequence of the on-shell meson rescattering. By analogy with those processes depicted by diagrams of Fig.1 these reactions may be considered as a two-step process when annihilation into 2,3,4,... mesons is followed by a meson absorption on one nucleon (see, Fig.4).

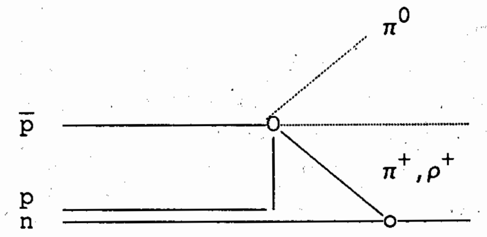

Fig.4

It is clear that such one-nucleon absorption of mesons is a rare process but it should exist in all channels of antiproton annihilation in nuclei where pions or kaons are created. It should be a common reaction of antiproton-nucleus annihilation in which two-nucleons are involved by definition.

The signatures of these reactions are quite definite and follow from the intrinsic two-body kinematics of the Pontecorvo reactions:

$$\bar{p} + 2N \Rightarrow M + N \qquad (10)$$

which implies the strict relation between the total momentum of the meson system P_{tot} and its effective mass M_{eff}.

Crude estimations of the total probability of all Pontecorvo reactions in $\bar{p}$ A annihilation give

$$W = \sum_{m} W(N\bar{N} \Rightarrow m\pi) * S_m . \qquad (11)$$

Here $W(N\bar{N} \Rightarrow m\pi)$ is the branching ratio of the corresponding annihilation channel with m pions and S_m is the probability that a pion will be absorbed on one nucleon. As an estimate for the value of S_m one may use the ratio of $W(\bar{p} + d \Rightarrow \pi^- + p)$ to $W(\bar{p} + p \Rightarrow \pi^- + \pi^+)$ which is about 10^{-2}. Then from (11) one may conclude that it is reasonable to expect for the probability of all Pontecorvo reactions the value at the level of at least 1% of all annihilations. So the Pontecorvo reactions are by no means some rare and exotic channels of $\bar{p}$A annihilation. They should be quite usual and especially important for the high-momentum part of the $\bar{p}$A annihilation spectrum.

There is a lot of interesting physical problems which could be explored by investigation of the Pontecorvo reactions. A good example is the search for the so called C-meson with the mass of 1480 MeV andthe width $\Gamma = 130 \pm 60$ MeV ($J^{PC} = 1^{--}$) . This state was observed [17] in the effective mass spectrum of $\Phi\pi^0$ system from the reaction

$$\pi^- + p \text{ --- } (K^+ K^- \pi^0)\, n \qquad (12)$$

at 32.5 GeV/c.

The authors [17] stressed as the exclusive property of the C the fact that it was not observed in the $\omega\pi$ channel. That indicates on the strange contents of the C-meson. Dover and Fishbane [18] argued that the C-meson is a good candidate for the four-quark exotic system of $s\bar{s}q\bar{q}$ type. That is the reason why the investigation of the C-meson properties and decay modes is rather important. However the experimental situation with search for the C-meson is rather controversial. In some experiments there are indications of its observation (for review, see [19]), in others the absence of any signal was claimed [20,21]. In particular, recently the ASTERIX collaboration [21] did not observe the C-meson in $\bar{p}p$ annihilation at rest in the $\Phi\pi\pi$ mode with the upper level of 3 10^{-5}.

From the decay scheme of the C-meson it follows that its isospin is I=1 and it is possible to search for charged states of the C in the Pontecorvo reaction of $\bar{p}$ annihilation on deuterium:

$$\begin{aligned} \bar{p} + d \Rightarrow C(1480)^- &+ p \\ \Rightarrow \Phi &+ \pi^- \\ \Rightarrow K^+ &+ K^- . \end{aligned} \qquad (13)$$

The merits of searching for the C-meson in this reaction are the following:

1.The absence of the combinatorial background. In the $\bar{p}p \Rightarrow \Phi\pi\pi$ reaction one never knows which pion comes from C-decays and which one recoils against the C.

2.The absence of the background from the meson resonance decays. Thus, in antiproton annihilation on hydrogen at rest , in the $\bar{p}p \Rightarrow \Phi\pi\pi$ channel, the probability of the $\bar{p}p \Rightarrow \Phi\rho^0$ mode contributes about 50% of all $\Phi\pi\pi$ yield. That impedes the search for the C-meson if its yield is less than that for $\Phi\rho$ channel.

3. Two-body kinematics of (13) allows one to have definite signatures for this reaction. The simulation shows that the proton momentum is peaked at 703 MeV/c with r.m.s.=78 MeV/c. All protons are within the 500-800 MeV/c interval. So they can be disentangled from the ordinary spectator protons and could be identified by time-of-flight.

The kaon momentum in the lab system is peaked at 330 MeV/c with r.m.s= 124 MeV/c. All kaon momenta are less than 600 MeV/c. The angle between two kaons is 43^0 with the r.m.s=23 degrees. Practically all kaons are in the angular interval between 0 and 90 degrees. The angle between a kaon and a proton is 141^0 with r.m.s

24^0. All events are in the interval from 85 to 180 degrees. The pion angular distributions are broad.

So, in fact, there is a correlation between two kaons which are in the narrow cone and a high-momentum proton which is emitted in the opposite direction.

To search for the C-meson in the reaction (13) looks very promising and challenging. The OBELIX detector at LEAR [5] is especially suitable for this task due to its good abilities of separation between kaons and pions.

Summarizing one may conclude that the investigation of the Pontecorvo reactions can be essential in the clarifying the role of non-nucleonic degrees of freedom in the nuclei as well as be a good tool for search for exotic resonances. The analysis of the Pontecorvo reactions can clarify the role of two-nucleon annihilation in the antiproton interactions with nuclei.

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