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L.A. Kondratyuk, M.G. Sapozhnikov

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PONTECORVO REACTIONS OF TWO-BODY ANTIPROTON ANNIHILATION IN DEUTERIUM

L.A. KONDRATYUK [a,b] and M.G. SAPOZHNIKOV [a]

[a] *Joint Institute for Nuclear Research, Laboratory of Nuclear Problems, Dubna, Head Post Office, P.O. Box 79, 101 000 Moscow, USSR*

[a,b] *Institute for Theoretical and Experimental Physics, 117 259 Moscow, USSR*

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Rare annihilation reactions for stopped antiprotons in deuterium $\bar{p}d \to \pi^- p$, $K^+\Sigma^-$, $K^0\Lambda$ are considered using the two-step model described by the triangle diagram. It was found that the probabilities W of these processes are very sensitive to the behaviour of the deuteron wave function at small distances as well as to the meson form factors. It appears that the ratios $R(KX) = W(KX)/W(\pi^- p)$ are much less model-dependent and are about 10^{-2} for $R(K^0\Lambda)$ and 10^{-4} for $R(K^+\Sigma^-)$.

As early as 1956, just half a year after the discovery of the antiproton, Pontecorvo drew attention [1] to the possibility of unusual annihilation processes forbidden on a free nucleon but allowed on bound nucleons. These are the annihilation reactions with only one meson in the final state:

$$\bar{p}+d \to \pi^- + p\,, \qquad (1)$$

$$\bar{p}+d \to K^+ + \Sigma^-\,, \qquad (2)$$

$$\bar{p}+d \to K^0 + \Lambda\,, \qquad (3)$$

or annihilation without any mesons at all:

$$\bar{p}+{}^3He \to p+n\,, \qquad (4)$$

$$\bar{n}+{}^3He \to p+p\,. \qquad (5)$$

Unfortunately, practically, the Pontecorvo reactions have not been investigated up to now. Only reaction (1) has been observed [2,3] in antiproton annihilation at rest. At a recent LEAR experiment [3] it was found that the relative probability of (1) was $W(\pi^- p) = (2.8 \pm 0.3) \times 10^{-5}$ of the total probability of $\bar{p}d$ annihilation. The upper limit on the relative probability of reaction (2): $W(K^+\Sigma^-) < 8 \times 10^{-6}$ was also determined [3] for stopped antiprotons. The mesonless annihilation processes (4), (5) have not been observed yet.

The interest in studying the Pontecorvo reactions (1)–(5) is mainly motivated by their sensitivity to high momentum components of the nuclear wave function, where quark–gluon degrees of freedom may play an important role (see, cf. refs. [4,5]). Let us illustrate this statement considering the two-step annihilation mechanism of the triangle diagrams of fig. 1. After antiproton annihilation on a nucleon in the deuteron two high-energy mesons with $T_{kin} \approx m_N$ are created, one of the mesons being absorbed on a sec-

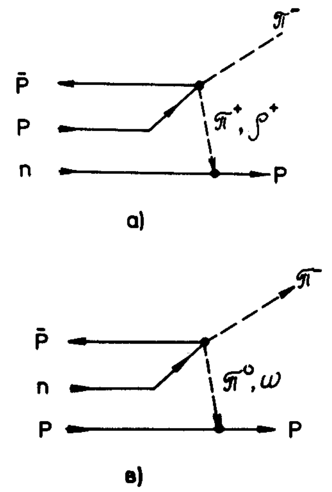

Fig. 1. Diagrams describing the two-step mechanism of the reaction $\bar{p}+d \to \pi^- + p$.

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ond nucleon of the deuteron. It is clear that this process cannot conserve energy–momentum at each step and the virtuality of the particles in the intermediate state should be very considerable $\approx m_N$. Thus the amplitude must be very sensitive to the small internucleon distances in the deuteron.

We have calculated the probability of reactions (1)–(3) using the two-step model (see figs. 1a and 1b). The preliminary results of our analysis were published in ref. [5] (the diagram of fig. 1a has mainly been analysed).

Under the assumption that the two-meson annihilation amplitude $\bar{N}N \to M^+M^-$ exhibits a smoother momentum dependence than the deuteron wave function one may obtain the following:

$$F(\bar{p}d \to MN) = F(\bar{p}N \to M^+M^-) A_\Delta . \tag{6}$$

The meson absorption amplitude A_Δ from (6) was calculated according to the usual rules of the nonrelativistic diagram technique (see, e.g. ref. [6]), where integration over the energy in the matrix element is reduced to the evaluation of the residue of the function under the integral in the positive energy pole of the neutron propagator $(p_2^2 - m_2^2 + i\epsilon)^{-1}$. In the deuteron rest frame one may obtain

$$A_\Delta = 2\sqrt{m}\, g_{MNN} \int \frac{d^3 p_2}{(2\pi)^3} \psi_d(\boldsymbol{p}_2) \times \frac{F_{MNN}(\boldsymbol{p}_2, \boldsymbol{k})}{-\delta_0(\boldsymbol{p}_2^2 + \boldsymbol{p}_2 \boldsymbol{k} + \beta_M(\boldsymbol{p}_1, M))} , \tag{7}$$

where

$$\delta_0 = 1 + (T_1 + \Delta m)/m , \tag{8}$$

$$\boldsymbol{k} = -2\boldsymbol{p}_1/\delta_0 , \tag{9}$$

$$\beta_M(\boldsymbol{p}_1, M) = [\boldsymbol{p}_1^2 + M^2 - (T_1 + \Delta m)^2]/\delta_0 . \tag{10}$$

Here T_1, p_1 and m_1 are the kinetic energy, momentum and mass of the final state baryon: $\Delta m = m_1 - m$ is the difference between the hyperon and nucleon masses in reactions (2) and (3), for reaction (1) $\Delta m = 0$. Note that in the nonrelativistic limit the amplitude (7) is purely real because the nucleon m and the meson M cannot be simultaneously on the mass shell.

To clarify the main features of the Pontecorvo reactions let us treat (7) under the assumption that the deuteron wave function has a more sharp dependence on $\boldsymbol{p}_2$ as compared with the form factor F_{MNN} and the meson propagator, then we find

$$A_\Delta = 2\sqrt{m}\, g_{MNN} \psi_d(r \to 0) F_{MNN}(\boldsymbol{p}_2 = 0, \boldsymbol{k}) \times [-\delta_0(\beta_M(\boldsymbol{p}_1, M))]^{-1} . \tag{11}$$

One can see that A_Δ depends strongly on the behaviour of the deuteron wave function ψ_d at small internucleon distances. However $\psi_d(r) \to 0$ when $r \to 0$, therefore the Pontecorvo reactions should also be sensitive to the meson–nucleon form factor $F_{MNN}(q^2)$ at large q^2. We used the following MNN form factors $F_{MNN}(q^2)$:

$$F_{MNN}(q^2) = [(M^2 - \Lambda_n^2)/(q^2 - \Lambda_n^2)]^n , \tag{12}$$

with $n = 1$ or 2 (monopole or dipole form factors) and $\Lambda_1^2 = 1.44\ \text{fm}^2$, $\Lambda_2^2 = 0.71\ \text{fm}^2$.

In the case of vector meson absorption in the intermediate state we take only the charge-like MNN interaction into account.

The relative probability of one-meson annihilation is

$$W_p(\bar{p}d \to pM^-) = W(\bar{p}p \to M^+M^-) \kappa |A_\Delta|^2 . \tag{13}$$

Here

$$\kappa = \frac{\sigma_{ann}(\bar{p}p)}{\sigma_{ann}(\bar{p}d)} \frac{p^*_{\pi^-}\, p^*_{\bar{p}p}\, S_N}{p^*_{\pi^+}\, p^*_{\bar{p}d}\, S_d} , \tag{14}$$

where $p^*_{\pi^-}$ and $p^*_{\pi^+}$ are the CMS momenta of the mesons in the final state of the reactions $\bar{p}d \to p\pi^-$ and $\bar{p}p \to M^+M^-$, respectively. Here S_N, $p^*_{\bar{p}p}$ (S_d, $p^*_{\bar{p}d}$) are the total energy and the CMS momentum of the $\bar{p}N$ ($\bar{p}d$)-system. It follows from the data [7] that around the threshold $\sigma_{ann}(\bar{p}p)/\sigma_{ann}(\bar{p}d) = 0.552$. Then the coefficient κ for reaction (1) is $\kappa = 0.247$.

The P-wave structure of the MNN vertex in the case of pion absorption can be taken into account by substituting $|A_\Delta|^2$ for $|A_\Delta|^2$ in (13)

$$A_\Delta = \sqrt{2m}\, g \frac{\boldsymbol{k}}{m_1} \int \frac{d^3 p_2}{(2\pi)^3} \psi(\boldsymbol{p}) \times \frac{F_{MNN}(\boldsymbol{p}_2, \boldsymbol{k}) \boldsymbol{P}\boldsymbol{k}/k^2}{-\delta_0(\boldsymbol{p}_1)[\boldsymbol{p}_2^2 + \boldsymbol{p}_2\boldsymbol{k} + \beta_M(\boldsymbol{p}_1, M)]} , \tag{15}$$

where $g_{\pi^+ np} = \sqrt{2}\, g_0$, $g_0^2/4\pi = 14$, $\boldsymbol{P} = 2m_1[\boldsymbol{p}_1/(E_1 + m_1) - \boldsymbol{p}_2/(E_2 + m_2)]$.

One must also consider the contribution from annihilation on the neutron (fig. 1b). As found in ref.

[8], the S-wave is dominant in the $\bar{\mathrm{N}}\mathrm{N}\to\pi\pi$ annihilation amplitude near threshold. It implies that the isovector state is the main one here. Then it is easy to calculate the total contribution of the diagrams in figs. 1a and 1b:

$$W(\bar{\mathrm{p}}\mathrm{d}\to\pi^-\mathrm{p})=4W_{\mathrm{p}}(\pi^-\mathrm{p})\,, \tag{16}$$

where $W_{\mathrm{p}}(\pi^-\mathrm{p})$ stands for the probability of annihilation on the proton (diagram of fig. 1a).

In the calculation of the πp-channel contribution we consider the annihilation on the proton only because according to ref. [9] 84% of antiproton annihilations at rest in the reaction $\bar{\mathrm{p}}\mathrm{p}\to\pi\mathrm{p}$ come from the $^{13}\mathrm{S}_1$, isospin $I=0$ state.

Reaction (2) may proceed only via annihilation on the proton. Both annihilation diagrams are important in reaction (3). Let us write the answer via $W_{\mathrm{p}}(\mathrm{K}^0\Lambda)$ which corresponds to the annihilation on the proton (fig. 1a):

$$W(\bar{\mathrm{p}}\mathrm{d}\to\mathrm{K}^0\Lambda)=\eta^2W_{\mathrm{p}}(\mathrm{K}^0\Lambda)\,, \tag{17}$$

where

$$\eta=|(3A_1-A_0)/(A_1-A_0)|\,. \tag{18}$$

A_1 and A_0 are the isovector and isoscalar amplitudes of $\bar{\mathrm{N}}\mathrm{N}\to\mathrm{K}\bar{\mathrm{K}}$. Bearing in mind the result of ref. [10] on the small interference between the amplitudes A_0 and A_1 in the S-state and using the data on the $\bar{\mathrm{p}}\mathrm{p}(\bar{\mathrm{p}}\mathrm{n})$ annihilation into $\mathrm{K}\bar{\mathrm{K}}$ [11] one may obtain that $\eta^2\approx4$.

Table 1 shows the results of the calculation of the probability of reaction (1) for different deuteron wave functions and form factors $F_{\mathrm{MNN}}(q^2)$ from (12). Branching ratios for different two-meson channels $W(\mathrm{N}\bar{\mathrm{N}}\to\mathrm{M}_1\mathrm{M}_2)$ were taken from ref. [11].

One can see that the results are strongly model dependent. Nevertheless, some common conclusions may be drawn:

(i) For all $\psi_{\mathrm{d}}(p)$ and $F_{\mathrm{MNN}}(q^2)$ the contributions from ρ- and ω-meson absorptions seem to be small (two orders of magnitude) in comparison with pion absorption.

(ii) The sensitivity of the results to the choice of $F_{\mathrm{MNN}}(q^2)$ is substantial. The steeper dependence on q^2, the less the probability $W(\bar{\mathrm{p}}\mathrm{d}\to\pi^-\mathrm{p})$.

(iii) The probability of (1) calculated with the realistic $\psi_{\mathrm{d}}(p)$ and MNN form factor is always less than the experimental result. For example, calculations with the Paris wave function and the dipole form factor gives $W(\bar{\mathrm{p}}\mathrm{d}\to\pi^-\mathrm{p})=2.7\times10^{-6}$.

The reason for this suppression are the strong oscillations of the realistic wave functions $\psi_{\mathrm{d}}(p)$ at large momenta ($p\approx1$ GeV/c), which are relevant in the Pontecorvo reactions. Such oscillations arise due to the NN repulsive core result in $\psi_{\mathrm{d}}(r)\to0$ at $r\to0$ (see eq. (11)). The quark degrees of freedom should lead to nonzero values of $\psi_{\mathrm{d}}(r)$ at small distances owing to the tunnelling of the quarks between different nucleon bags. (Notice, that eq. (11) looks like the result that followed from the reduced QCD formalism proposed by Brodsky [4]). Qualitatively, this situation is imitated by the Hulthèn wave function which anomalously slowly decreases at large p. As one can see in table 1, the calculation with the Hulthèn wave function and the dipole form factor demonstrates reasonable agreement with the experimental data. Of course, this agreement should not be overestimated.

A similar treatment of the diagrams of fig. 1, which includes some relativistic corrections was done in ref. [14]. However, in ref. [14] the calculations were performed only with the Hulthèn wave function and

Table 1
The relative probability W of the reaction $\bar{\mathrm{p}}+\mathrm{d}\to\pi^-\mathrm{p}$, calculated for Paris [12], Reid soft core [13] and Hulthèn deuteron wave functions.

Probability	Paris	Reid	Hulthèn	F_{MNN}
$W(\pi^-,\pi^+)$	5.7×10^{-6}	9.2×10^{-6}	1.4×10^{-3}	monopole
$W(\pi^-,\rho^+)$	3.9×10^{-8}	1.1×10^{-10}	3.5×10^{-5}	monopole
$W(\pi^-,\omega)$	5.8×10^{-8}	1.4×10^{-11}	4.7×10^{-5}	monopole
$W(\pi^-,\pi^+)$	2.7×10^{-6}	1.0×10^{-6}	4.1×10^{-5}	dipole
$W(\pi^-,\rho^+)$	1.8×10^{-10}	5.9×10^{-11}	3.3×10^{-9}	dipole
$W(\pi^-,\omega)$	1.1×10^{-10}	3.8×10^{-11}	2.2×10^{-9}	dipole
experiment:	$W(\bar{\mathrm{p}}\mathrm{d}\to\pi\mathrm{p})=(0.9\pm0.6)\times10^{-5}$ [a] $=(2.8\pm0.3)\times10^{-5}$ [b]			

[a] Ref. [2]. [b] Ref. [3].

for the monopole form factor. It was found that $W(\bar{p}d\to\pi^-p)=1.5\times10^{-4}$. According to Oset [15] using the realistic Bonn deuteron wave function leads also to the decrease of $W(\bar{p}d\to\pi^-p)$ [#1].

The branchings of one-meson annihilation with a strange meson are also strongly model-dependent. Though, the ratios R of the probabilities of reactions (2) and (3) to that of (1) do not vary too much with the model used and may be regarded as a guide for future experiments. For example, using the Paris wavefunction it was found that $R(K^+\Sigma^-)=W(K^+\Sigma^-)/W(\pi^-p)=2.7\times10^{-4}$ and $R(K^0\Lambda)=1.1\times10^{-2}$ whereas using the Hulthèn wave function the corresponding ratios are $R(K^+\Sigma^-)=1.7\times10^{-4}$ and $R(K^0\Lambda)=0.8\times10^{-2}$. In all variants the probability of reaction (2) is less than that of reaction (3) because the $(K\Sigma N)$ coupling constant is smaller than the $(K\Lambda N)$ one.

Using the calculated ratios R and the experimental value for $W(\bar{p}d\to\pi^-p)$ [3] we can obtain the following predictions:

$$W(\bar{p}d\to K^+\Sigma^-)=7.6\times10^{-9},$$
$$W(\bar{p}d\to K^0\Lambda)=3.1\times10^{-7}. \qquad (19)$$

Therefore, the two-step mechanism for the one-strange-meson annihilation provides probabilities that are by one–three orders of magnitude lower than the experimental upper limit $W(K^+\Sigma^-)<8\times10^{-6}$ [3]. The discovery of these reactions at the level of 10^{-6}–10^{-7} would be a clear signal of nontrivial physics.

For example, in ref. [16] the yields of reactions (2), (3) were calculated in the model of the evaporation of a fireball with nonzero baryon charge. It was found that $W(\bar{p}d\to K^+\Sigma^-)=(7.8\pm0.8)\times10^{-6}$, and $R(K^0\Lambda)=0.29$. These results are in strong contrast with the predictions of the two-step model (19). Further experiments in this field with greater statistics will be very desirable.

In conclusion, in the framework of nonrelativistic diagram techniques for the two-step mechanism, the probabilities of the reactions of one-meson antiproton annihilation at rest in deuterium have been calculated. It was found that these processes are very sensitive to the deuteron wave function at small distances, as well as to the meson form factors. The calculations with realistic $\psi_d(k)$ result in the probability of $W(\bar{p}d\to\pi\bar{p})$ being an order of magnitude lower than the experimental value. This result may indicate the importance of quark degrees of freedom in the deuteron wave function. It appears that the ratios $W(KX)/W(\pi\bar{p})$ are much less model-dependent and are about 10^{-2} for $R(K^0\Lambda)$ and 10^{-4} for $R(K^+\Sigma^-)$.

It is clear that an increase in the energy of the antiproton gives the opportunity to study the deuteron wave function at momenta greater than 1 GeV/c in the Pontecorvo reactions. Searching for the Pontecorvo reactions, which is planned at the OBELIX detector at LEAR, may provide this unique information.

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[#1] It must be stressed that in ref. [14] there was an erroneous statement that our calculation [5] takes into account only the on-shell meson absorption. In fact, this contribution is simply zero in the framework of the nonrelativistic formalism which we used. Our calculations consider only the virtual meson absorption. This contribution is the dominant one as shown in ref. [14].

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