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PONTECORVO REACTIONS OF TWO-BODY ANTIPROTON ANNIHILATION IN DEUTERIUM

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

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

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

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

or annihilation without any mesons at all:

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

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

Unfortunately the Pontecorvo reactions have not been practically investigated up to now. Only reaction (1) has been observed. In the experiment [2] 6 events of reaction (1) were found in the antiproton annihilation at rest. The corresponding relative probability of (1) was $W(\pi^- p) = (0.9 \pm 0.4) \cdot 10^{-5}$ of the total probability of $\bar{p}d$-annihilation. Recently reaction (1) has been measured in the LEAR experiment [3], where it was found that $W(\pi^- p) = (2.8 \pm 0.3) \cdot 10^{-5}$, and the upper limit on the relative probability of reaction (2): $W(K^+\Sigma^-) < 8 \cdot 10^{-6}$ was found for the stopped antiprotons. The mesonless annihilation processes (4)-(5) have not been observed yet.

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, c.f. [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 second 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.1 a) and b)). The preliminary results of our analysis were published in [5] (the diagram of Fig.1 a) has been mainly analysed).

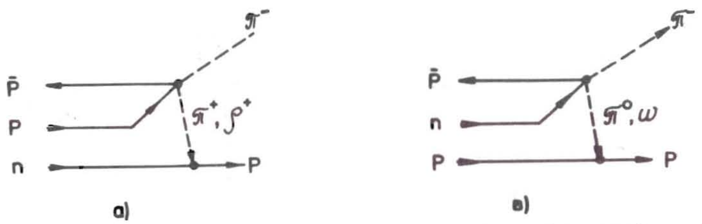

Fig.1 Diagrams of the two-step model for the reaction (1)

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:

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

where A_Δ is the meson absorption amplitude described by the triangle diagram of Fig. 1a):

$$A_\Delta = i \int \frac{g_{MNN}(q^2)\, d^4p_2}{(2\pi)^4} \frac{G_{dnp}((p_2-p_3)/2)}{(p_2^2 - m_2^2 + i\varepsilon)(p_3^2 - m_3^2 + i\varepsilon)(q^2 - M^2 + i\varepsilon)}. \qquad (7)$$

Here p_2, p_3 are the momenta of the neutron and proton, $g_{MNN}(q^2)$ is the MNN vertex function, $G_{dnp}(p)$ is related to the deuteron wave function $\psi_d(p)$ as follows:

$$G_{dnp}(\vec{p}) = 8\, m^{5/2}\, \psi_d(\vec{p})\, (\varepsilon_b + \vec{p}^{\,2}/m), \qquad (8)$$

here ε_b is the deuteron binding energy, m and M are the nucleon and meson masses, respectively. We used only the S-state of the deuteron wave function.

The amplitude A_Δ from (7) was calculated according to usual rules of the nonrelativistic diagram technique (see, e.g.[6]). Then the nucleon propagator may be treated as follows:

$$(p_j^2 - m_j^2 + i\varepsilon)^{-1} = (E_j - \sqrt{\vec{p}_j^{\,2} + m_j^2 +} \, i\varepsilon)^{-1} (E_j + \sqrt{\vec{p}_j^{\,2} + m_j^2} + i\varepsilon)^{-1} \approx$$
$$\approx (2\, m_j\, (T_j - \vec{p}_j^{\,2}/2m_j + i\varepsilon)^{-1}, \qquad (9)$$

where E_j and T_j stand for the total and kinetic energy of the nucleon j .

Integration of (7) over the energy is reduced to the evaluation of the residue in the positive energy pole of the neutron propagator $(p_2^2 - m_2^2 + i\varepsilon)^{-1}$. After that, in the deuteron rest frame :

$$A_\Delta = 2\sqrt{m} \int \frac{d^3p_2}{(2\pi)^3}\, \psi_d(\vec{p}_2)\, \frac{g_{MNN}(q^2)}{q^2 - M^2 + i\varepsilon}, \qquad (10)$$

where

$$q^2 - M^2 = -\delta_o(\vec{p}_1)\,(p_2^2 + \vec{p}_2\vec{k} + \beta_M(\vec{p}_1, M)) \qquad (11)$$

$$\delta_o(\vec{p}_1) = 1 + (T_1 + \Delta m)/m \qquad (12)$$

$$\vec{k} = -2\,\vec{p}_1/\delta_o \qquad (13)$$

$$\beta_M(\vec{p}_1, M) = \frac{\vec{p}_1^{\,2} + M^2 - (T_1^* + \Delta m)^2}{\delta_o}. \qquad (14)$$

Here T_1, $\vec{p}_1$ 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) -(3) , for reaction (1) $\Delta m = 0$. Note that in the nonrelativistic limit the amplitude (7) is pure real because the nucleon m and the meson M cannot be simultaneously on the mass shell.

Finally, eq. (10) may be rewritten as:

$$A_\Delta = 2\sqrt{m}\, g_{MNN} \int \frac{d^3p_2}{(2\pi)^3}\, \psi_d(\vec{p}_2)\, \frac{F_{MNN}(\vec{p}_2, \vec{k})}{-\delta_o\,(\vec{p}_2^{\,2} + \vec{p}_2\,\vec{k} + \beta_M(\vec{p}_1, M))}. \qquad (15)$$

To clarify the main features of the Pontecorvo reactions let us treat (15) under the assumption that the deuteron wave function has more sharp dependence on $\vec{p}_2$ as compared with the form factor F_{MNN} and meson propagator. Then we find:

$$A_\Delta = 2\sqrt{m}\, g_{MNN}\, \psi_d(r \to 0)\, \frac{F_{MNN}(\vec{p}_2 = 0, \vec{k})}{-\delta_o\,(\beta_M(\vec{p}_1, M))}. \qquad (16)$$

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 $F_{MNN}(q^2)$:

$$F_{MNN}(q^2) = [(M^2 - \Lambda_n^2)/(q^2 - \Lambda_n^2)]^n \qquad (17)$$

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

Expression (15) was also used to calculate the contribution from the vector meson absorption in the intermediate state. The interaction of vector mesons with nucleons is described by two constants f_1 and f_2

$$\bar u \left(f_1 \gamma_\mu + f_2 \frac{\sigma_{\mu\nu} q_\nu}{2 m} \right) u . \qquad (18)$$

In our estimations we confine ourselves by taking into account only the charge-like interaction and put $g_{MNN} = f_1$.

If the $\bar N N \to \pi^+\pi^-$ annihilation proceeds in the S-wave (from the $^{33}S_1$ state), then π -mesons are in the P-wave and the spin structure of the amplitude (6) is of the form $\psi^*(p_1)(\vec P\ \vec\sigma)(\vec\sigma\ \vec\varepsilon_d^{(m)})(\vec\sigma\ \vec K)\ \psi(\bar p)$, where

$$\vec P = 2 m_1(\vec p_1/(E_1 + m_1) - \vec p_2/(E_2 + m_2)),$$

$\varepsilon_d^{(m)}$ is the vector of deuteron polarization, $\vec K$ is the relative momentum of π-mesons , $\psi(\bar p)$ stands for the antiproton spinor: $\psi = i\sigma_2\psi_T^*$.

It means that in the case of pion absorption instead of the scalar A_Δ (15) we have to introduce the vector amplitude

$$\vec A_\Delta = \sqrt{\frac{2m}{m_1}}\ g_{MNN}\ \vec k \int \frac{d^3p_2}{(2\pi)^3}\ \psi(\vec p_2) \frac{F_{MNN}(\vec p_2,\vec k)\ \vec P\vec k/\vec k^2}{-\delta_o(\vec p_1)(\vec p_2^{\,2} + \vec p_2\vec k + \beta_M(\vec p_1, M))}, \qquad (19)$$

where $g_{\pi^+ np} = \sqrt{2}\ g_o$, $g_o^2/4\pi = 14$.

Then, calculating the probability we should average the amplitude squared over the spin projections of the antiproton and the deuteron.

Therefore, the P-wave structure of MNN vertex in the case of pseudoscalar meson absorption can be taken into account by substituting $|\vec A_\Delta|^2$ instead of $|A_\Delta|^2$.

The amplitudes from (6) are normalized in a standard way:

$$\frac{d\sigma}{dt}(\bar pN \to M^+M^-) = \frac{1}{64\pi S_N}\ \frac{1}{p_{\bar pp}^{*2}}\ |F(\bar pN \to M^+M^-)|^2$$

$$\frac{d\sigma}{dt}(\bar pd \to p M^-) = \frac{1}{64\pi S_d}\ \frac{1}{p_{\bar pd}^{*2}}\ |F(\bar pd \to p M^-)|^2 . \qquad (20)$$

Here S_N , $p^*_{\bar pp}$ (S_d, $p^*_{\bar pd}$) are the total energy and the c.m.s. momentum of the $\bar pN(\bar pd)$ -system.

The relative probability of one-meson annihilation is:

$$W_p(\bar pd \to p M^-) = \frac{\sigma(\bar pd \to p M^-)}{\sigma_{ann}(\bar pd)} = \qquad (21)$$

$= W(\bar pp \to M^+M^-)\ \varkappa\ |A_\Delta|^2$ - in the case of vector meson absorption

$= W(\bar pp \to M^+M^-)\ \varkappa\ |\vec A_\Delta|^2$ - in the case of pseudo-scalar meson absorption .

Here

$$\varkappa = \frac{\sigma_{ann}(\bar pp)}{\sigma_{ann}(\bar pd)}\ \frac{p^*_{\pi^-}\ p^*_{\bar pp}\ S_N}{p^*_{\pi^+}\ p^*_{\bar pd}\ S_d}, \qquad (22)$$

where $p^*_{\pi^-}$ and $p^*_{\pi^+}$ are the c.m.s. momenta of the mesons in the final state of the reactions $\bar pd \to p\ \pi^-$ and $\bar pp \to M^+ M^-$, respectively.

It follows from the data [7] that near the threshold $\sigma_{ann}(\bar pp)/\sigma_{ann}(\bar pd) = 0.552$. Then the coefficient $\varkappa$ for reaction (1) is equal to 0.247.

One must also consider the contribution from annihilation on the neutron (Fig.1b). In reaction (1), for instance, it is possible to create a pair $\pi^-\pi^0$ ($\bar pn \to \pi^-\pi^0$) followed by π^0 absorption. As found recently in the experiment [8], the S-wave is dominant in the $\bar NN \to \pi\pi$ annihilation amplitude near the threshold. It implies that here the isovector state is the main one. Then it is easy to calculate the total contribution of diagrams in Fig.1a) and 1b) :

$$W(\bar{p}d \to \pi^- p) = 4\, W_p(\bar{p}d \to \pi^- p), \qquad (23)$$

where $W_p(\bar{p}d \to \pi^- p)$ stands for the probability of annihilation on the proton (diagram of Fig. 1a)).

In the calculation of the $\pi\rho$-channel contribution we consider only the annihilation on the proton because according to [9] 84% of events of annihilation of antiprotons at rest in the reaction $\bar{p}p \to \pi\rho$ come from the $^{13}S_1$ state with the isospin I=0. It is clear that the contribution from the ω -meson absorption is due to the diagram of Fig. 1b) of the annihilation on the neutron.

Reaction (2) may proceed only via annihilation on the proton. Both annihilation diagrams are important in reaction (3). Let us write the answer via $W_p(K^o\Lambda)$ which corresponds to the annihilation on the proton (Fig. 1a)):

$$W(\bar{p}d \to K^o\Lambda) = \eta^2\, W_p(K^o\Lambda), \qquad (24)$$

where

$$\eta = |(3A_1 - A_o)/(A_1 - A_o)|, \qquad (25)$$

A_1 and A_o are the isovector and isoscalar amplitudes of $\bar{N}N \to \bar{K}K$. Bearing in mind that [10,13]

$$\frac{W(\bar{p}p \to K^+K^-)}{W(\bar{p}n \to K^-K^o)} = \frac{|A_1 - A_o|^2}{4\,|A_1|^2} = 0.65 \pm 0.11 \qquad (26)$$

and using the data of [10] on small interference between the amplitudes A_o and A_1 in the S-state one may find:

$$\eta^2 \approx 4. \qquad (27)$$

In Table 1 the branching ratios of different $\bar{N}N$ annihilation channels into two mesons used in our calculation are collected.

Table 1. Relative probabilities W of different two meson $\bar{N}N$ annihilation channels for the stopped antiprotons.

Channel	$\pi^+\pi^-$	$\pi^-\rho^+$	$\pi^-\omega$	K^-K^+	$K^o\bar{K}^o$
W (%)	0.37±0.03	1.35±0.2*)	0.41±0.08	0.096±0.008	0.08±0.05
Refs.	11	12	13	11	11

*) In [12] the branching ratio of $\pi^{\pm}\rho^{\mp}$ was measured but there is an indication that $\pi^-\rho^+$ is about a half of $\pi^{\pm}\rho^{\mp}$.

Table 2 shows the results of the calculation of the probability of reaction (1) for different deuteron wave functions and form factors $F_{MNN}(q^2)$.

Table 2. The relative probability W of the reaction $\bar{p} + d \to \pi^- + p$, calculated for Paris [14], Reid soft core [15] and Hulthen deuteron wave functions.

	PARIS	REID	HULTHEN	F_{MNN}
$W(\pi^-,\pi^+)$	$5.7\cdot10^{-6}$	$9.2\cdot10^{-6}$	$1.4\cdot10^{-3}$	monopole
$W(\pi^-,\rho^+)$	$3.9\cdot10^{-8}$	$1.1\cdot10^{-10}$	$3.5\cdot10^{-5}$	monopole
$W(\pi^-,\omega)$	$5.8\cdot10^{-8}$	$1.4\cdot10^{-11}$	$4.7\cdot10^{-5}$	monopole
$W(\pi^-,\pi^+)$	$2.7\cdot10^{-6}$	$1.0\cdot10^{-6}$	$4.1\cdot10^{-5}$	dipole
$W(\pi^-,\rho^+)$	$1.8\cdot10^{-10}$	$5.9\cdot10^{-11}$	$3.3\cdot10^{-9}$	dipole
$W(\pi^-,\omega)$	$1.1\cdot10^{-10}$	$3.8\cdot10^{-11}$	$2.2\cdot10^{-9}$	dipole

Experiment: $W(\bar{p}\,d \to \pi^- p) = (0.9\pm 0.6)\cdot 10^{-5}$ [2]
$= (2.8\pm 0.3)\cdot 10^{-5}$ [3]

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

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

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

iii) The probability of (1) calculated with the realistic $\psi_d(p)$ 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 $W(\bar{p}d \to \pi^- p) = 2.7\cdot10^{-6}$

The reason for this suppression is the strong oscillations of the realistic wave functions $\psi_d(p)$ at large momenta ($p \approx 1$ GeV/c), which are relevant in the Pontecorvo reactions. Such oscillations arise due to the NN repulsive core result in $\psi_d(r) \to 0$ at $r \to 0$ (see eq.(16)). The quark degrees of freedom should lead to the nonzero values of $\psi_d(r)$ at small distances owing to the tunnelling of the quarks between different nucleon bags.(Note, that eq. (16) looks like the result followed from the reduced QCD formalism proposed by Brodsky

[4]). Qualitatively, this situation is imitated by the Hulthen wave function which anomalously slowly decreases at large p . As one can see in Table 2, the calculation with the Hulthen 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 [16]. However, in [16] the calculations were performed only with the Hulthen wave function and for the monopole formfactor. It was found that $W(\bar{p}d \to \pi^- p) = 1.5 \cdot 10^{-4}$. According to E.Oset private communications, using the Bonn deuteron wave function also leads to the decrease of $W(\bar{p}d \to \pi^- p)$ *).

The branchings of one-meson annihilation with strange meson production (2)-(3) are collected in Table 3.

Table 3. The relative probabilities W of reactions $\bar{p} + d \to K^+ + \Sigma^-$, $K^0 + \Lambda$ calculated for the Paris [14] and Hulthen deuteron wave functions. The values R of the ratio of the probabilities of reactions (2) and (3) to that of (1) $R = W(K,X) / W(\pi^- p)$ are also given.

	PARIS	HULTHEN	F_{MNN}
$W(K^+ + \Sigma^-)$	$5.0 \cdot 10^{-9}$	$5.2 \cdot 10^{-7}$	monopole
$W(K^0 + \Lambda)$	$1.5 \cdot 10^{-7}$	$2.7 \cdot 10^{-5}$	monopole
$W(K^+ + \Sigma^-)$	$7.3 \cdot 10^{-10}$	$7.1 \cdot 10^{-9}$	dipole
$W(K^0 + \Lambda)$	$3.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-7}$	dipole
$R(K^+\Sigma^-)$	$8.8 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$	monopole
$R(K^0\Lambda)$	$2.6 \cdot 10^{-2}$	$1.9 \cdot 10^{-2}$	monopole
$R(K^+\Sigma^-)$	$2.7 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	dipole
$R(K^0\Lambda)$	$1.1 \cdot 10^{-2}$	$7.6 \cdot 10^{-3}$	dipole

Experiment: $W(\bar{p}\, d \to K^+\Sigma^-) < 8 \cdot 10^{-6}$; $R(K^+\Sigma^-) < 0.29$ [3].

*) It must be stressed that in [16] 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 [16].

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 a model and may be regarded as a guide for future experiments. For example, using the Paris wave function it was found that $R(K^+\Sigma^-) = W(K^+\Sigma^-) / W(\pi^- p) = 2.7 \cdot 10^{-4}$ and $R(K^0\Lambda) = 1.1 \cdot 10^{-2}$ whereas using the Hulthen wave function the corresponding ratios are $R(K^+\Sigma^-) = 1.7 \cdot 10^{-4}$ and $R(K^0\Lambda) = 0.8 \cdot 10^{-2}$. 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:

$$W(\bar{p}d \to K^+\Sigma^-) = 7.6 \cdot 10^{-9}$$
$$W(\bar{p}d \to K^0\Lambda) = 3.1 \cdot 10^{-7}. \qquad (28)$$

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

For example, in [17] the yields of reactions (2)-(3) were calculated in the model of evaporation of a fireball with the nonzero baryon charge. It was found that $W(\bar{p}d \to K^+\Sigma^-) = (7.8 \pm 0.8) \cdot 10^{-6}$, and $R(K^0\Lambda) = 0.29$. These results are in a strong contrast with the predictions of the conventional triangle diagram (28) . Further experiments in this field with greater statistics will be very desirable.

In conclusion, in the framework of nonrelativistic diagram techniques for 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 $\psi_d(p)$ result in the probability of $W(\bar{p}d \to \pi^- p)$ 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 $W(KX)/W(\pi^- p)$ 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 an 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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Реакция Понтекорво двухчастичной $\bar{p}d$-аннигиляции

В рамках нерелятивистской диаграммной техники выполнен расчет реакций одномезонной аннигиляции антипротонов на дейтерии. Показано, что характеристики этой реакции очень чувствительны к виду волновой функции дейтрона на малых расстояниях и выбору мезонных формфакторов. Расчеты с реалистической $\Psi_d(k)$ приводят к значениям $W(\bar{p}d \to \pi^- p)$ на порядок меньшим экспериментального, что может служить указанием на существенный вклад кварковых степеней свободы в таких процессах. Показано, что отношение вероятностей $R(KX)=W(KX)/W(\pi^- p)$ слабо зависят от модельных предположений и их величина составляет 10^{-2} для $R(K^0\Lambda)$ и 10^{-4} для $R(K^+\Sigma^-)$.

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Pontecorvo Reactions of Two-Body Antiproton Annihilation in Deuterium

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 probilities, 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 $R(K^+\Sigma^-)$.

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

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