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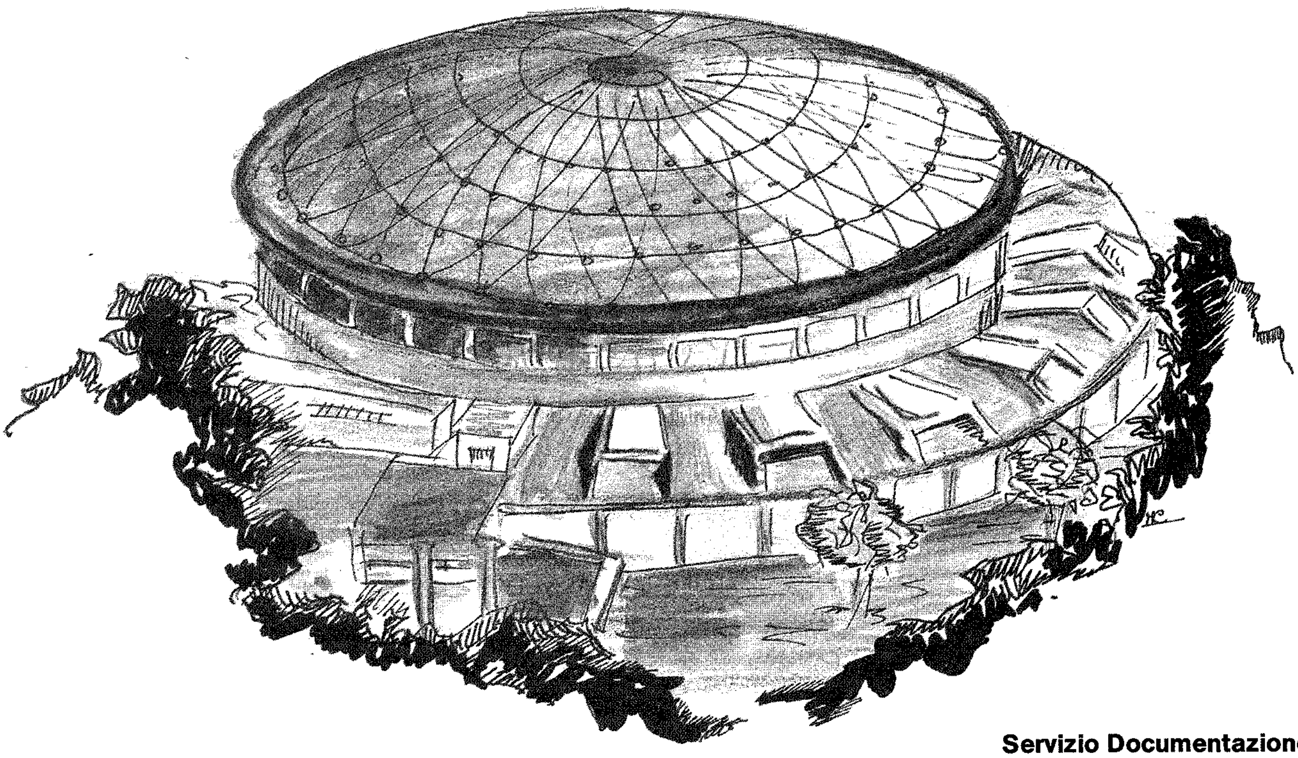

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PONTECORVO REACTIONS OF TWO-BODY ANNIHILATIONS $\bar{P}D$ AND $\bar{P}$ ^3HE AND MULTIQUARK STATES IN D AND ^3HE

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ABSTRACT

We discuss the probabilities of the Pontecorvo reactions $\bar{p}^3He \rightarrow pn$ and $\bar{p}d \rightarrow \pi^- p$ at rest and relate them to the admixtures of multiquark states in d and ^3He. The treatment is relativistic and is based on the reduced QCD amplitude approach proposed by Brodsky. According to our estimation, the ratio $R=\sigma(\bar{p}\,^3He \rightarrow pn)/\sigma(\bar{p}d \rightarrow \pi^- p)$ is $\lesssim 10^{-3}$ for stopped antiprotons.

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Just after the discovery of antiproton Bruno Pontecorvo considered unusual annihilation processes forbidden on a free nucleon but allowed on nucleons bound in nuclei [1].

We compare here the probabilities of two Pontecorvo reactions

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

$$\bar{p}\ {}^3He \to pn \tag{2}$$

and discuss their sensitivity to the admixtures of multiquark states in d and ^3He.

The probability of the reaction (1) was calculated in ref. [2] using the nonrelativistic two-step model described by the triangle graph of Fig. 1, where the first step is the production of two mesons in the antiproton annihilation on one nucleon and the second step is the absorption of the virtual meson by the second nucleon (see also ref. [3]).

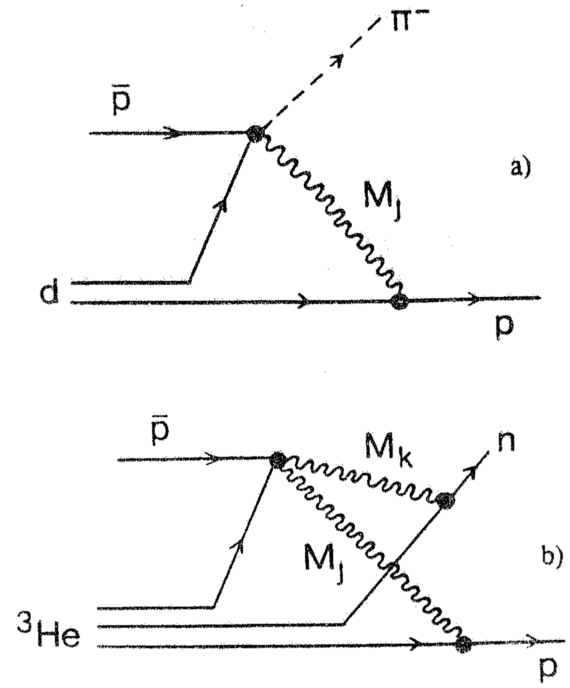

FIG.1 - Diagrams describing the two-step mechanism of the reactions $\bar{p}d\to\pi^-p$ (a) and $\bar{p}\ {}^3He\to pn$ (b). M_j and M_k are the effective mesons (or glueballs) exchanged after the initial $\bar{p}p$ annihilation.

In the static limit, when the nucleon (antinucleon) mass m_N is very large ($m_N\to\infty$) the amplitude of the reaction (1) is proportional to the deuteron wave function $\psi_d\,(r\to0)$. As for realistic models of deuteron, due to the repulsive core, $\psi_d(r)\to0$ when $r\to0$.

However, from the point of view of quark models, it would be very unnatural to expect that $\Psi_d(r)\to0$ when $r\to0$. Indeed, the tunneling of quarks between nucleons should lead to nonzero value of $\Psi_d(r)$. In quark models even the meaning of the core may be quite different. For example, in the quark compound bag model [4] all the effects which are attributed to the nuclear core are in fact related to the non locality and energy dependence of the NN potential generated by the formation of 6q-bag.

As the probabilities of the reactions (1) and (2) are sensitive to small internucleon distances, it would be important to take into account the quark degrees of freedom. In ref. [5] it was proposed to describe the large Q_T behavior of reaction (1) (large energy and fixed c.m. angle θ) using the quark dimensional counting rules [6] according to which, at $Q_T >> m^2$

$$\frac{d\sigma}{dt} (\bar{p}d \rightarrow \pi^- p) \sim \frac{1}{(Q_T^2)^{12}} f (\theta_{c.m.}) \tag{3}$$

It is unlikely, however, that these rules could be applied at $Q_T{}^2 \cong 1$ (GeV/c)^2. In this case better estimates can apparently be made using the QCD reduced amplitude approach [7].

As it was argued in ref. [5], this approach can describe the elastic scattering of electron from deuteron and the electrodisintegration of deuteron beginning from $Q^2 \cong 1$ (GeV/c)^2. Here we shall apply it to estimate the relative probability of the reactions (1) and (2).

Let us consider the amplitude of the reaction $\bar{p}d \rightarrow \pi^- p$ at large momentum transfer, in correspondence with diagram of Fig. 1, which we shall calculate in the infinite momentum frame.

In the QCD reduced amplitude approach the deuteron is considered as a system of two weakly bound nucleons where each one carries one half of the total momentum and we can write

$$A^j_{\bar{p}d} (s, t) = A^j_{\bar{p}p} (s_1, t) \frac{2m_N g_j F_j (q_1^2)}{q_1^2 - m_j^2} \Delta_d \tag{4}$$

Here $A^j_{\bar{p}p}(s_1, t)$ is the amplitude of the reaction $\bar{p}p \rightarrow \pi^- M_j$; m_j and g_j denote the mass and coupling constant for the meson (or glueball) state M_j which transfers large momentum between upper and lower parts of the diagram in Fig. 1a; k_1, k_2, k_3 and k_4 are the four momenta of $\bar{p}$, d, π^- and p respectively; $s = (k_1 + k_2)^2$, $t = (k_1 - k_3)^2$, $q_1 = k_4 - k_2/2$, $s_1 = (k_1 + 1/2\ k)^2$; F_j is the nucleon form factor in the vertex M_jNN.

The deuteron structure factor Δ_d is given by the expression

$$\Delta_d = \int \frac{d^2 \mathbf{k}_\perp\, dx}{(2\pi)^3\, 2x\,(1 - x)} \psi_{rel} (\mathbf{k}_\perp, x) \tag{5}$$

In deriving the eqs. (4) and (5) we have used the reference frame where $\mathbf{k}_{2\perp} = 0$.
The internal light-cone variables $\mathbf{k}_\perp$ and $x = (\varepsilon_k + k_z)/2\varepsilon_k$ describe the transverse relative (pn) momentum and the fraction of the longitudinal deuteron momentum which is carrried by a neutron in the infinite momentum frame, $\varepsilon_k = (\mathbf{k}^2 + m_N^2)^{1/2}$.

As it was argued in refs. [8,9] the relativistic deuteron light cone w.f. $\psi_{rel}(\mathbf{k}_\perp, k_z)$ can be related to the phenomenological nonrelativistic parametrizations of $\psi_d(\mathbf{k})$ by the expression

$$\psi_{rel}(\mathbf{k}_\perp, k_z) = \sqrt{2\varepsilon_K}\, \Psi_d(\mathbf{k}) \tag{6}$$

Therefore we can write

$$\Delta_d = \int \frac{d^3k}{(2\pi)^3\sqrt{2\varepsilon_k}} \psi_d(\mathbf{k}) = \frac{1}{\sqrt{2m_N}}\, \psi^d_{eff}(r=0) \tag{7}$$

Note that in the nonrelativistic limit $\Delta_d \to (2m_N)^{-1/2}\psi_d(r=0)$. The factor $(2\varepsilon_k)^{-1/2}$ leads to the relativistic smearing.

In ref. [2] the amplitude $A^j_{\bar{p}d}(s_1,t)$ was calculated in nonrelativistic approach for $j = \pi, \rho$ and ω. The contribution of ρ-meson found there is incorrect because the ρNN interaction of the type $\sigma_{\mu\nu} q_\nu$ was neglected. On the other hand, in ref. [3] the π – and ρ– exchanges were calculated using nonconsistent treatment of the graph of Fig. 1a in nonrelativistic approach. In fact the imaginary part of this graph which was taken into account in ref.[3] and corresponds to the singularity of meson propagator should be cancelled by the contributions of other singularities, which in ref [3] were neglected. To demonstrate this one should start directly from the relativistic 4–dimensional expression for the graph of Fig. 1 and calculate it, for example in the infinite momentum frame (see e.g. the discussion of the triangle graph corresponding to the deuteron form factor in refs [8,9]). In the light cone energy variable $P_- = (E_p - P_3)/\sqrt{2}$ the diagram of Fig.1a has only 3 poles: the contribution of neutron pole is equal to the sum of meson and proton pole contributions and the result is given by eqs. (4) – (5).

Taking into account π–, ρ– and ω – contributions, we get

$$\left| \sum_j A^j_{\bar{p}d} \right|^2 = 4\, C_0 \left| A^\pi_{\bar{p}d} \right|^2 \tag{8}$$

where the amplitude $A^\pi_{\bar{p}d}$ describes the channel $\bar{p}\, d \to \pi^-\pi^+ n \to \pi^- p$.

The factor C_0 in the noncoherent approximation is given by

$$C_0 = 1 + \frac{f^2_\rho\, m^2_\pi}{4 f^2_\pi\, m^2_\rho} \left(\frac{t_1 - m^2_\pi}{t_1 - m^2_\rho} \right)^2 B(\rho/\pi) + \frac{f^2_\omega\, m^2_\pi}{8 f^2_\pi\, m^2_\omega} \left(\frac{t_1 - m^2_\pi}{t_1 - m^2_\omega} \right)^2 B(\omega/\pi) \tag{9}$$

where $B(\rho/\pi) = \dfrac{B(\bar{p}p\to\rho^+\pi^-)}{B(\bar{p}p\to\pi^+\pi^-)} \approx 3.65$; $B(\omega/\pi) = \dfrac{B(\bar{p}n\to\omega\pi^-)}{B(\bar{p}p\to\pi^+\pi^-)} \approx 1$;

$f_\pi^2/4\pi = 0.08$; $f_{\pi^+ np} = \sqrt{2}\, f_\pi$; $f_\rho = 9.3$; $f_\omega = 6.5$ (see e.g. ref. [10]).

The coefficent $\frac{1}{4}$ in the ρ-meson contribution is due to the fact that the s-wave amplitude $\bar{p}p\to\pi^-\rho^+$ is predominantly isoscalar [11,12], while the s-wave amplitude $\bar{p}p\to\pi^-\pi^+$ is isovector [11,12]. Because of pseudoscalar character of πNN interaction the constant g_π^2 in eq. (8) should be substituted by $f_\pi^2\, q_1^2 / m_\pi^2$. As we took the values of coupling constants from ref. [10] we have to take also their form factors which are the monopole ones.

Comparing the calculated value of $B(\bar{p}\, d\to \pi^- p)$ at rest with experimental data (1.4 ± 0.7) 10^{-5} [13] we find

$$|\psi_d^{eff}(0)|^2 \cong (1\div3)\cdot 10^{-5}\ \mathrm{GeV}^3 \qquad (10)$$

Originally in ref. [7] it was proposed to use the dipole form factors which would be in better correspondence with QCD asymptotics.The dipole form factors are certainly relevant for photon exchanges. As for the meson exchanges at moderate q^2 their form factors might be quite different from the asymptotical form predicted by QCD. If we take the dipole form factor we would receive unrealistically large value of $|\psi_d^{eff}(0)|^2$.

Let us compare this result with the prediction of the hybrid model of deuteron:

$$|d\rangle = \sqrt{1-P_B}\,|NN\rangle + \sqrt{P_B}\,|6q\rangle \qquad (11)$$

In ref. [14] the static properties of the deuteron were analyzed for the case of nonuniversal bag constant B. One solution which was found in ref. [14] corresponds to the admixture of 6q bag $P_B = 5.8\%$ with $R_{6q}^{rms} = 0.688$ fm and the critical distance between two nucleons when they fuse into 6q-bag $r_o = 1.06$ fm. For the Gaussian parametrization of two-baryon component of the 6q-bag

$$\psi_B(r) = (\sqrt{\pi}\, b)^{-3/2} \exp(-r^2/2b^2), \quad b = \sqrt{\frac{2}{3}}\, R_{6q}^{rms} \qquad (12)$$

we get

$$|\psi_d^{eff}(0)|^2 = P_B\,|\psi_B(0)|^2 \approx 6\cdot 10^{-5}\ \mathrm{GeV}^3 \qquad (13)$$

which is several times larger than the value given in eq. (10). However, if we take $r_0 = 0.7$ fm, then $P_B \approx 0.73\%$ and we find $|\psi_d^{eff}(0)|^2 = 2.6 \cdot 10^{-5}\,\mathrm{GeV}^3$, which is in good agreement with eq. (10). Therefore the value of $|\psi_d^{eff}(0)|^2$ extracted from the data on $B(\bar{p}d \to \pi^- p)$ can be related to the contribution of 6q-bag in deuteron. Considering the amplitude $\bar{p}^3He \to pn$ corresponding to Fig. 1b in the same approach, we find

$$A^{jk}_{\bar{p}^3He}(s', t) = A_{\bar{p}p}(s_2, t')\, M^{jk}(t_1', t_2') \tag{14}$$

where $A^{jk}_{\bar{p}p}(s_2, t')$ is the amplitude of the two meson annihilation $\bar{p}p \to M_j M_k$,

$$M^{jk}(t_1', t_2') = \frac{2m_N g_j F_j(t_1')}{t_1' - m_j^2} \frac{2m_N g_k F_k(t_2')}{t_2' - m_k^2} \cdot \frac{1}{2m_N} \psi^{^3He}_{eff}(r_{12} = 0, r_{23} = 0), \tag{15}$$

$\psi^{^3He}_{eff}(r_{12} = 0, r_{23} = 0)$ is the ^{3}He wave function where all the internucleon distances are going to zero. Here:

$$s' = (k_1 + k_2')^2,\ t' = (k_1 - k_3')^2,\ t_1' = \left(\frac{1}{3} k_2' - k_3'\right)^2,\ t_2' = \left(\frac{1}{3} k_2' - k_4'\right)^2 \tag{16}$$

and the momenta of $\bar{p}$, ^{3}He, p and n are denoted as k_1, k_2', k_3' and k_4' respectively. The helium structure factor $\psi^{^3He}_{eff}(0,0)$ can be related to the admixture of 9q–bag in ^{3}He:

$$|\psi^{^3He}_{eff}(r_{12} = 0, r_{23} = 0)|^2 \approx 3 P^2_{6q} |\psi^{6q}_{eff}(0)|^4 \tag{17}$$

If for the estimate we take the critical distance between two nucleons in ^{3}He $r_0 = 1$fm, then, according to refs. [15-16], the value of P_{6q} in ^{3}He would be $(6 \div 8)\,\%$.

The ratio of the cross sections of reactions (1) and (2) can be written as

$$R = \frac{(d\sigma_{c.m.}/d\Omega)\ \bar{p}\,^3He \to pn}{(d\sigma_{c.m.}/d\Omega)\ \bar{p}d \to \pi^- p} = \frac{k_{pn}}{k_{\pi^- p}} \frac{s}{s'} \frac{\left|\sum_{jk} A^{jk}_{\bar{p}^3He}\right|^2}{\left|\sum_j A^j_{\bar{p}d}\right|^2} \tag{18}$$

where k_{pn} and $k_{\pi^- p}$ are the c.m. momenta of final proton-neutron and pion-neutron pairs, respectively. We take into account j,k = π,ρ and ω. It appears that the main contribution comes from the channels with two vector mesons. There are data in liquid hydrogen on the reaction $\bar{p}p \to \omega\rho^o$: $B(\bar{p}p \to \omega\rho^o) = (2.1 \pm 0.2)\%$ [17] or $(3.49 \pm 0.56 \pm 0.35)\%$ [11]. The two meson channel dominance model of ref. [18] predicts the branching ratios $B(\rho\rho) \cong B(\omega\rho^o) = (8 \div 8.5)\%$ and $B(\omega\omega) = 4.4\ \%$. We assume that the s-wave amplitude for $\bar{N}N$ annihilation into two vector mesons is isoscalar, then $B(\rho^+\rho^-) = 2\,B(\rho^o\rho^o) = \frac{2}{3}\,B(\rho\rho)$. For the estimation we take $B(\rho\rho) = B(\omega\rho^o) = B(\omega\omega) = 4\%$.

Then we find:

$$R = (0.7 \div 1.2) \cdot 10^{-3} \tag{19}$$

If all the meson contributions would add coherently the latter number can be about $3 \cdot 10^{-3}$.
Therefore our estimate for the ratio of the probabilities of the reactions (2) and (1) at rest is

$$R = (0.7 \div 3) \cdot 10^{-3} \tag{20}$$

This value could be 4÷6 times smaller if the critical distance r_o is about 0.7 fm.

It is interesting to compare the obtained prediction with that of the statistical model of Cugnon and Vandermeulen [19]. In this model the reaction $\bar{n}\,^3He \to pp$ proceeds in two steps:

i) the formation of a B = 2 fireball with the probability $P_B \approx 1\%$;

ii) the decay of fireball into NN system with the branching ratio $\approx 10^{-4}$.

Therefore Cugnon and Vandermeulen predict the yield of the reaction $\bar{n}\,^3He \to pp$ (which apparently should be almost the same as for $\bar{p}\,^3He \to pn$) to be about 10^{-6} and the ratio (20) to be about $R \approx 10^{-1}$. This represent a very striking difference from the prediction of our two-step model.

In other terms, the measurement of the Pontecorvo reaction $\bar{p}\,^3He \to pn$ or $\bar{n}\,^3He \to pp$ should allow to clearly *discriminate* between the two approaches. If the yield is that predicted by the statistical model, i.e.$\approx 10^{-6}$, the measurement should be feasible using the LEAR beam and in particular the OBELIX detector [20]. If the yield is much smaller, as is the indication of the two-step model, the reaction can not be detected using the $\bar{p}$ beams available now. In this case, it may be more realistic to measure the time reversed reaction $pp \to {}^3He\,\bar{n}$ using much more intense proton beams.

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