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AN INSIGHT INTO THE PARITY VIOLATION AT πNN VERTEX

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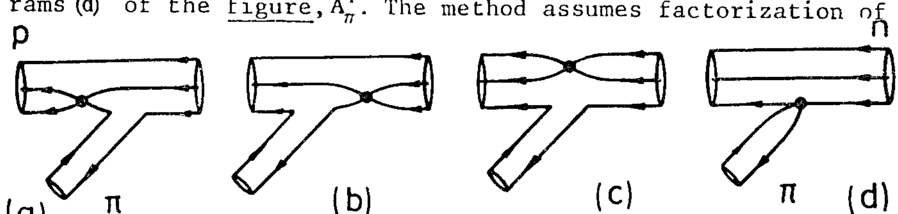
In this paper we consider the parity violating (PV) πNN vertex parametrized in the usual way

$$<\pi^- p | \mathcal{H}^{PV} | n> = i G m_\pi^2 A_\pi \phi_\pi \bar{u}_p u_n , \qquad (1)$$

where $\mathcal{H}^{PV}$ is the effective Hamiltonian of the PV hadron-hadron interactions. Interest in the constant A_π stems from the fact that it determines the long-range ($r \sim 1.4$ fm) part of the PV NN potential with $\Delta I = 1$. These properties enable A_π to be separated, for instance, from the experiments on observation of PV in the electromagnetic nuclear transitions. Taking into account the theoretical uncertainties while extracting from experiments, the value of A_π^{exp} is in the interval (1.5, 2.5)[1].

The theoretical evaluation of A_π is difficult because the Hamiltonian $\mathcal{H}^{PV}$ is formulated in terms of the quark operators. For the local hamiltonian $\mathcal{H}^{PV}$ the structure of the vertex (1) is shown in the figure. Two different methods are usually used to calculate A_π. The first one is based on the PCAC and SU(3)[2] and expresses a part of the amplitude (1), defined by the equal time commutator (ETC) in the standard technique of soft pions, A_π^{ETC}, through the ETC-parts of s-wave amplitudes of the decays $\Lambda^\circ \to \pi^- p$ and $\Xi^- \to \pi^- \Lambda^\circ$ with $\Delta S = 1$. However, this method can be applied just to the part $\mathcal{H}^{PV}_{\Delta S=0}$, which has the SU(3) partner in $\mathcal{H}^{PV}_{\Delta S=1}$. According to the estimates of ref.[3] $A_\pi^{ETC} \lesssim 1$.

The second method[4,3] allows one to calculate the part of the amplitude (1) which corresponds to the factorizing (F) diagrams (d) of the figure, A_π^F. The method assumes factorization of



Quark structure of the PV πNN vertex (1). The circle denotes the effective hamiltonian $\mathcal{H}^{PV}$; (a)-(c) are nonfactoriting (NF) and (d) factorizing (F) diagrams.

the amplitude (1) and applicability of free equations of motion to the quark fields. As a result, in A_π^F there appears a factor $f_\pi/(m_u+m_d)$ which amounts to ~10, if one uses the parameters of the chiral symmetry breaking $m_u+m_d \sim 10$ MeV [5] as quark masses. The obtained value of A_π^F is in the interval (1.5, 3.5) [3] and may pretend to the explanation of A_π^{exp}.

However, these methods of calculation of A_π have the following unclear points:

i) interpretation of A_π^{ETC} in terms of the diagrams of the figure;

ii) calculation of A_π^{ETC} for the *total* hamiltonian $\mathcal{H}^{PV}$ in the standard electroweak model $SU(2)_L \otimes U(1)$ (SEWM);

iii) dependence of the *observable* A_π on the *nonobservable* parameters m_u and m_d. We now proceed to consider these points.

I. Using PCAC, within the field-theoretical approach [6], one can show that the ETC-part of the amplitude (1) describes the nonfactorizing (NF) diagrams (a), (b) of the figure with $k_\pi \to 0$, whereas the NF diagram (c) vanishes in this limit. Thus, $A_\pi = A_\pi^{NF} + A_\pi^F$, where $A_\pi^{NF} \approx A^{ETC}$. The same can be referred to any amplitude $\langle \pi B' | \mathcal{H}^{PV} | B \rangle$, in particular to $A(\Lambda^0_-)$ and $A(\Xi^-_-)$. This conclusion justifies the arguments of papers [7,8] and is proved in the Appendix.

II. From point I and ref. [2] it follows that if the effective hamiltonian $\mathcal{H}^{PV}$ can be represented as

$$\mathcal{H}^{PV} = c_{\Delta S=1} \mathcal{O}^8_{\Delta S=1,\Delta I=1/2} + c_{\Delta S=0} \mathcal{O}^8_{\Delta S=0,\Delta I=1}, \quad \mathcal{O}^8_k \in 8, \qquad (2)$$

then

$$A_\pi^{NF} = -\sqrt{\frac{2}{3}} \frac{c_{\Delta S=0}}{c_{\Delta S=1}} [2A^{NF}(\Lambda^0_-) - A^{NF}(\Xi^-_-)], \qquad (3)$$

where

$$A^{NF}(H) = A^{exp}(H) - A^F(H).$$

Let us now show that owing to the penguin contributions [4] to the effective hamiltonian $\mathcal{H}^{PV}$ in the SEWM⊗QCD, the matrix elements $\langle \pi B' | \mathcal{H}^{PV} | B \rangle^{NF}$ in the valence quark approximation satisfy condition (2). In the SEWM⊗QCD in part of $\mathcal{H}^{PV}$ under consideration has the form [4,3]

$$\mathcal{H}^{PV} = \sqrt{2}\, G \sum_k (c^{27}\mathcal{O}^{27} + c^S\mathcal{O}^S + c^A\mathcal{O}^A + c^6\mathcal{O}^6 + c^5\mathcal{O}^5)_k \qquad (4)$$

Here k takes two values $k=(\Delta S=1)$ and $k=(\Delta S=0, \Delta I=1)$; c^r are the numerical coefficients, depending on the structure of weak and quark-gluon interactions; $\mathcal{O}^r$ are the local operators:

$$\{\underline{27}\}: \quad \mathcal{O}^{27}_{\Delta S=1} = \bar d d \bar d s + \bar s s \bar d s + \bar d s \bar d d + \bar d s \bar s s - 2(\bar d u \bar u s + \bar d s \bar u u + \bar u s \bar d u + \bar u u \bar d s) + h.c.,$$

$$\mathcal{O}^{27}_{\Delta S=0,\Delta I=1} = \frac{1}{2}(\bar u u \bar u u - \bar d d \bar d d - \bar u u \bar s s - \bar s s \bar u u + \bar d d \bar s s + \bar s s \bar d d) - \bar u s \bar s u + \bar d s \bar s d + h.c.,$$

$$\{\underline{8}\}: \quad \begin{bmatrix} \mathcal{O}^S \\ \mathcal{O}^A \\ \mathcal{O}^6 \\ \mathcal{O}^5 \end{bmatrix}_k = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} \mathcal{O}(\Lambda_k, 1) \\ \mathcal{O}^c(\Lambda_k, 1) \\ \mathcal{O}(1, \Lambda_k) \\ \mathcal{O}^c(1, \Lambda_k) \end{bmatrix},$$

where

$$\bar q_1 q_2 \bar q_3 q_4 = :\bar q_{1i} \gamma_\mu \gamma_5 q_{2i} \bar q_{3j} \gamma^\mu q_{4j}:, \quad \mathcal{O}(A,B) = \; :\bar q_i \gamma_\mu \gamma_5 A q_i \bar q_j \gamma^\mu B q_j:. \quad \mathcal{O}^c(A,B) = \; :\bar q_i \gamma_\mu \gamma_5 A q_j \bar q_j \gamma^\mu B q_i:,$$

the summation is assumed over the colour indices i and j; $\Lambda_k = \lambda_6$ at $k=(\Delta S=1)$ and $\Lambda_k = 1/2\,\lambda_3$ at $k=(\Delta S=0, \Delta I=1)$. The SU(3) properties of the operators are denoted in the braces. The typical values of the coefficients c^r are given in the table. We should like to recall that without the penguin contributions $c^6_{\Delta S=1} = c^5_{\Delta S=1} = 0$. Therefore, thanks to penguins *each* operator $\mathcal{O}^r_{\Delta S=0,\Delta I=1}$ in (4) acquires the SU(3) partner $\mathcal{O}^r_{\Delta S=1}$!

Table

Numerical values of the coefficient functions c^r at $\sin\theta_C = 0.23$, $\sin^2\theta_W = 0.23$, $\alpha_s(m_c)/\alpha_s(M_W) = 2.45$, $\alpha_s(R_c^{-1})/\alpha_s(m_c) = 3.71$ [9].

ΔS	c^{27}	c^S	c^A	c^6	c^5
1	−0.014	0.0049	0.15	0.0020	−0.012
0	0.029	−0.027	0.46	−0.029	−0.081

In the valence quark approximation for the matrix elements $<\pi B'|\mathcal{O}^r|B>^{NF}$ the following relations hold:

$$<\pi B'|\mathcal{O}^{27}|B>^{NF} = <\pi B'|\mathcal{O}^S|B>^{NF} = 0 \text{ /10/, and } <\pi B'|\mathcal{O}^5|B>^{NF} = -<\pi B'|\mathcal{O}^6|B>^{NF}$$

owing to antisymmetry of the quark wave functions in baryons; $<\pi^- p|\mathcal{O}^A_{\Delta S=0,\Delta I=1}|n> = 0$ as $\mathcal{O}^A_{\Delta S=0,\Delta I=1}$ contains the s-quark operators, and consequently, $\mathcal{O}^A_{\Delta S=1}$ does not contribute to the right-hand side of relation (3).

Thus, we have shown that the sum rule (3) can be applied to the *total* effective hamiltonian (4) with

$$\frac{c_{\Delta S=0}}{c_{\Delta S=1}} = \frac{(c^6 - c^5)_{\Delta S=0}}{(c^6 - c^5)_{\Delta S=1}} . \tag{5}$$

III. Finally, we consider the factorizing parts of the amplitudes

$$A^F_\pi = -\frac{4}{3}(c^6 + 3c^5)_{\Delta S=0} \frac{f_\pi}{m_u + m_d} \eta_n ,$$

$$A^F\begin{pmatrix}\Lambda^\circ_- \\ \Xi^-_-\end{pmatrix} = \sqrt{\frac{2}{3}}(-8c^{27} + 4c^S + 2c^A)_{\Delta S=1} \frac{f_\pi}{m^2_\pi} \begin{pmatrix} M_\Lambda - M_p \\ M_\Xi - M_\Lambda \end{pmatrix} + \tag{6}$$

$$+ \frac{4}{3}(c^6 + 3c^5)_{\Delta S=1} \frac{f_\pi}{m_u + m_d} \begin{pmatrix}\eta_\Lambda \\ \eta_\Xi\end{pmatrix} .$$

Here, we choose the value $\eta_n = <p|\bar{u}d|n> \approx 0.5$, $\eta_\Lambda = <p|\bar{u}s|\Lambda^\circ> \approx 0.6$, $\eta_\Xi = <\Lambda^\circ|\bar{u}s|\Xi^-> \approx 0.6$ (that is in agreement within the factor 2 with other estimates /4,3/), and concentrate our attention on the factor $f_\pi/(m_u + m_d)$. This factor appears in the calculation of the matrix element $<\pi^-|\bar{d}\gamma_5 u|0>$ using the free equations of motion $(i\gamma^\mu\partial_\mu - m_q)q = 0$, $q = u, d$ and the assumption that the form of these equations does not change in the presence of strong interactions /4/. There arises a question: "What meaning should be attributed to the masses m_q?"

If the quarks were really free, the use of current masses $m^\circ_q \sim 5$ MeV would be justified. The situation is different when the quarks are confined. In this case the role of m_q is played by the effective mass m^*_q, which bears the information on the quark confinement /11/. The mass m^*_q is not a universal characteristic of the quark q and depends on the problem under consideration. At that $m^*_q \sim R_c^{-1}$, where R_c is the radius of confinement, which is characteristic of this problem. Here are two examples of calculation of m^*_q in the simplest version of the MIT bag with $m^\circ_q = 0$ /12/

$$m^*_q = -\frac{i}{2}\partial^\mu <\pi^-|\bar{d}\gamma_\mu\gamma_5 u|0> / <\pi^-|\bar{d}\gamma_5 u|0> = \frac{2\omega}{3(\omega-1)} R_\pi^{-1} ,$$

$$m^*_q = -\frac{i}{2}\partial^\mu <p|\bar{u}\gamma_\mu\gamma_5 d|n> / <p|\bar{u}\gamma_5 d|n> = \frac{2\omega^2}{4\omega - 3} R_N^{-1} ,$$

where $\omega = 2.04$. We note that in both the cases the coefficients at R_c^{-1} do not differ strongly from unity. Hence, it follows that for the calculation of A^F, in (6) it is reasonable to choose $m^*_u = m^*_d \approx 200$ MeV that corresponds to $R_c = 1$ fm. In this case $f_\pi/(m_u + m_d) = 1/2 f_\pi R_c \approx 0.23$ and A^F_π practically vanishes.

Now we can calculate the amplitude A_π. Substituting the values of c^r from the table into formulae (6), (5) and (3), we get

$$A_\pi = A^{NF}_\pi + A^F_\pi \approx A^{NF}_\pi \approx 3.5 .$$

The obtained A_π is 1.5-2 times as large as the average value of A^{exp}_π /8/, that is, in our opinion, due to the approximations /4,9/ which have been adopted in the calculation of the coefficient functions c^r of the effective hamiltonian $\mathcal{H}^{PV}$. The coefficients $c^6_{\Delta S=1}$ and $c^5_{\Delta S=1}$, which are determined by the behaviour of the QCD running constant $\alpha_s(\mu)$ at $\mu \lesssim m_c$ (m_c is the mass of c-quark), are especially sensitive to such approximations. Thus, the amplitude A_π may serve as a "touchstone" for the study of the quark-gluon interactions at large distances.

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APPENDIX

Here we give the field-theoretical description of the amplitude $<\pi B'|\mathcal{H}^{PV}|B>$ (part A) and show that the ETC-part of this amplitude corresponds to the diagrams (a) and (b) of the figure with $k_\pi \to 0$ (part B).

A. We write down the effective hamiltonian $\mathcal{H}^{PV}$ in the form

$$\mathcal{H}^{PV} = \sqrt{2}\, G \sum_{M,N} c^{MN} \mathcal{O}^{MN} ,$$

where $\mathcal{O}^{MN} = :\bar{q}Mq\bar{q}Nq:$, M and N are the matrices in the (spinor) $\otimes$ (flavour) $\otimes$ (colour) space, and consider the matrix elements $\mathcal{A} = \langle\pi B'|\mathcal{O}^{MN}|B\rangle$. Using the reduction formula and PCAC, we get

$$\mathcal{A} = \frac{i(-k_\pi^2+m_\pi^2)}{f_\pi m_\pi^2}\int d^4x\, e^{ik_\pi x}\langle B'|\partial^\mu T(:\bar{q}(x)P_\mu q(x):, \otimes\, \mathcal{O}^{MN}(0)) - \tag{A1}$$

$$-\,\delta(x^\circ)[:\bar{q}(x)P_0 q(x):,\ \mathcal{O}^{MN}(0)]|B\rangle ,$$

where $P_\mu = \gamma_\mu\gamma_5\frac{\lambda}{2}$, λ is the matrix defining the pion isotopic properties.

Expand the T-product and commutator in (A1) according to the Wick theorem

$$\partial^\mu T(:\bar{q}(x)P_\mu q(x):, \mathcal{O}^{MN}(0)) = T_9(x)+T_6(x)+T_6'(x)+T_3(x), \tag{A2}$$

$$T_9(x) = i:\bar{q}(x)P q(x)\bar{q}(0)Mq(0)\bar{q}(0)Nq(0):, \tag{a}$$

$$T_6(x) = :[\bar{q}(0)MS^c(-x)Pq(x)+\bar{q}(x)PS^c(x)Mq(0)]\bar{q}(0)Nq(0): + \{M\leftrightarrow N\}, \tag{b}$$

$$T_6'(x) = -\delta^4(x):[\bar{q}(0)M\gamma_0P_0q(x)+\bar{q}(x)\gamma_0P_0Mq(0)]\bar{q}(0)Nq(0): + \{M\leftrightarrow N\}, \tag{c}$$

$$T_3(x) = \partial^\mu[\,Sp(S^c(-x)P_\mu S^c(x)M):\bar{q}(0)Nq(0): - :\bar{q}(0)MS^c(-x)P_\mu S^c(x)Nq(0):] + \tag{d}$$

$$+\{M\leftrightarrow N\}\ ;$$

$$[:\bar{q}(x)P_0q(x):, \mathcal{O}^{MN}(0)] = C_6(x) + C_3(x), \tag{A3}$$

$$C_6(x) = -i:[\bar{q}(x)P_0S(x)Mq(0) - q(0)MS(-x)P_0q(x)]\bar{q}(0)Nq(0): + \{M\leftrightarrow N\}, \tag{a}$$

$$C_3(x) = [Sp(S^+(x)MS^-(-x)P_0) - Sp(S^+(-x)P_0S^-(x)M)]:\bar{q}(0)Nq(0): + \tag{b}$$

$$+:\bar{q}(0)[MS^+(-x)P_0S^-(x)N - MS^-(-x)P_0S^+(x)N]q(0): + \{M\leftrightarrow N\},$$

where the following notation is used: $P = \gamma_5\{m_q^*, \frac{\lambda}{2}\}$; $S^c(x) = i\langle 0|T(q(x),\bar{q}(0))|0\rangle$; $S^+_{\beta\alpha}(x) = i\langle 0|\bar{q}_\alpha(0)q_\beta(x)|0\rangle$, $S^-_{\alpha\beta}(x) = i\langle 0|q_\alpha(x)\bar{q}_\beta(0)|0\rangle$, $S(x) = S^+(x)+S^-(x)$.

The subscripts of the operators T(x) and C(x) denote their *operator* dimensions.

We introduce the matrices Q and R through the Fierz transformation

$$M_{AB}\otimes N_{CD} = Q_{AD}\otimes R_{CB}\,.$$

Then from (A1), (A2d), (A3b) and relations

$$\langle 0|T(:\bar{q}(x)P_\mu q(x):, :\bar{q}(0)Lq(0):)|0\rangle = Sp(S^c(-x)P_\mu S^c(x)L),$$

$$\langle 0|[:\bar{q}(x)P_0q(x):, :\bar{q}(0)Lq(0):]|0\rangle = Sp(S^+(x)LS^-(-x)P_0) -$$

$$-\,Sp(S^+(-x)P_0S^-(x)L), \qquad L = M,N,Q,R,$$

we find

$$\frac{i(-k_\pi^2+m_\pi^2)}{f_\pi m_\pi^2}\int d^4x\, e^{ik_\pi x}\langle B'|T_3(x)-\delta(x^\circ)C_3(x)|B\rangle =$$

$$= \langle\pi|:\bar{q}(0)Mq(0):|0\rangle\langle B'|:\bar{q}(0)Nq(0):|B\rangle - \langle\pi|:\bar{q}(0)Qq(0):|0\rangle\langle B'|:\bar{q}(0)Rq(0):|B\rangle +$$

$$+\{M\leftrightarrow N, Q\leftrightarrow R\}. \tag{A4}$$

Noting now that from $S(x)|_{x^\circ=0} = i\gamma^\circ\delta^3(x)$ it follows

$$\int d^4x\, e^{ik_\pi x}\langle B'|T_6'(x)-\delta(x^\circ)C_6(x)|B\rangle = 0, \tag{A5}$$

we get the final expression

$$\mathcal{A} = \frac{i(-k_\pi^2+m_\pi^2)}{f_\pi m_\pi^2}\int d^4x\, e^{ik_\pi x}\langle B'|T_9(x)+T_6(x)|B\rangle + \mathcal{A}^F\ , \tag{A6}$$

where the factorizing part of the amplitude $\mathcal{A}$, $\mathcal{A}^F$ is defined by expression (A4).

The comparison of (A2a,b) and (A6) with the diagrams of the figure shows that the matrix element of the operator T_9 corresponds to the diagram (c), and the matrix element of T_6 to the diagrams (a) and (b). As is seen from (A2a), the matrix element of the operator T_9 vanishes at $k_\pi \to 0$, and consequently, the diagrams (a) and (b) dominate in the nonfactorizing part of the amplitude $\mathcal{A}$, $\mathcal{A}^{NF}$.

B. By definition $\mathcal{A}^{ETC} = \lim_{k_\pi\to 0}\mathcal{A}$.

According to the canonical current algebra

$$\mathcal{A}^{ETC} = -\frac{i(-k_\pi^2+m_\pi^2)}{f_\pi m_\pi^2}\int d^4x\, e^{ik_\pi x}\delta(x^\circ)\langle B'|C_6(x)|B\rangle\Big|_{k_\pi\to 0}\ . \tag{A7}$$

It should be mentioned now that as $k_\pi \to 0$

$$\int d^4x\, e^{ik_\pi x} \langle B' | T_6(x) + T_6'(x) | B \rangle \to 0 .$$

Hence and from relations (A7) and (A5), we get immediately

$$\mathcal{A}^{ETC} = \frac{i(-k_\pi^2 + m_\pi^2)}{f_\pi m_\pi^2} \int d^4x\, e^{ik_\pi x} \langle B' | T_6(x) | B \rangle |_{k_\pi \to 0} ,$$

i.e., $\mathcal{A}^{ETC}$ corresponds to the diagrams (a) and (b) with $k_\pi \to 0$, and since the diagram (b) in this limit valishes, $\mathcal{A}^{ETC} = \mathcal{A}^{NF} |_{k_\pi \to 0}$.

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Новый взгляд на несохранение четности в πNN вершине

Рассмотрена нарушающая четность амплитуда $A_\pi = A(n \to \pi^- p)$. В рамках теоретико-полевого подхода показано, что каноническая ETC-часть A_π соответствует нефакторизационным (NF) диаграммам. A_π^{NF} может быть вычислена для полного эффективного гамильтониана теории $SU(2)_L \otimes U(1) \otimes SU(3)_C$ с помощью $SU(3)$ правила сумм и оказывается очень чувствительной к поведению бегущей константы QCD $\alpha_s(\mu)$ при $\mu \lesssim m_c$ / m_c - масса c-кварка/. Приведены аргументы, согласно которым вклад факторизационных диаграмм в A_π пренебрежимо мал.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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An Insight into the Parity Violation at πNN Vertex

$A_\pi = A(n \to \pi^- p)$ parity-violating amplitude is considered. Within the field-theoretical approach it is shown that canonical ETC-part of A_π corresponds to nonfactorizing (NF) diagrams. A_π^{NF} may be calculated for the total effective Hamiltonian in $SU(2)_L \otimes U(1) \otimes SU(3)_C$ theory via the $SU(3)$ sum rule and is very sensitive to the behaviour of running QCD constant $\alpha_s(\mu)$ at $\mu \lesssim m_c$ (m_c is mass of c-quark). It is argued that the contribution of factorizing diagrams into A_π is negligible.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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