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PHENOMENOLOGICAL CHIRAL LAGRANGIAN METHOD AND NONLEPTONIC DECAYS OF STRANGE AND CHARMED BARYONS

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I. Introduction

At present the original experimental data on nonleptonic weak decays of the charmed baryons became available [1]. But there is no yet satisfactory theoretical description of these decays. In fact, the phenomenological models based on Weinberg – Salam theory, QCD, bag models and current algebra have many free parameters, particularly when the three - or more - body decays are considered. In addition they lead to the contradictory results [2-5]. Nevertheless, it is useful to have reliable if rough branching ratio estimates for a more effective measurement and analysis of the experiment.

In this paper we propose to use the phenomenological chiral Lagrangian method (PCLM) for that purpose. The PCLM is based on the nonlinear realization of spontaneously broken chiral symmetry $SU_n \times SU_n$ with the vacuum stability group SU_n (n=2,3,4,...). The meaning of the nonlinear realization is that the Goldstone fields (the 0^- mesons) are identified with the symmetry group parameters corresponding to the generators which are not bounded by the conservation laws. The PCLM reproduces the current algebra results [5] in the "tree" approximation. As a rule, the PCLM does not contain free parameters except the physical values as masses, coupling constants, a.o.

This method has been successfully used to describe the hadronic low - energy processes [6] and generalized to the charmed mesons [7]. In the paper [8] the strong interaction chiral symmetry $SU_4 \times SU_4$ effective Lagrangian has been constructed. It should be noted that PCLM attracts attention of physics in view of the first successful attempts of many authors to deduce the chiral effective Lagrangians from QCD as the low - energy limit [9]. In addition, Witten has recently calculated the baryon static characteristics on the basis of the nonlinear solutions of chiral dynamics [10].

The paper is organized as follows. In section II we construct the phenomenological Lagrangians. In section III the two-body nonleptonic weak decay amplitudes are calculated. The results are discussed in section IV.

II. The phenomenological Lagrangians.

Our calculations of the two-body nonleptonic decay amplitudes of baryons are based on the following Lagrangian

$$\mathcal{L} = \mathcal{L}_S^{MM} + \mathcal{L}_S^{MB} + \mathcal{L}_W + \mathcal{L}_W^{BB} .$$

The term $\mathcal{L}_S^{MM}$ is the effective chiral $SU_4 \times SU_4$ meson-meson strong interaction Lagrangian having the form [7]

$$\mathcal{L}_S^{MM} = \frac{F_\pi^2}{4} \mathrm{Tr}(\partial_\mu M \partial^\mu M^+) + m_F^2 F_\pi^2 (e^{-i\lambda_{14}\Theta_c} M e^{i\lambda_{14}\Theta_c})_{44} ,$$

where M is the 4x4-matrix of the 15-plet of 0^- mesons, $F_\pi \simeq 93$ MeV is the pion leptonic decay constant, m_F is the mass of F meson, and Θ_c is the Cabibbo angle.

The chiral $SU_4 \times SU_4$ meson-baryon strong interaction Lagrangian, $\mathcal{L}_S^{MB}$, has the following form: [8]

$$\mathcal{L}_S^{MB} = \bar{B}(i\gamma_\mu \mathcal{D}^\mu - m_o)B - g_A[\alpha(\bar{B}\gamma_\mu\gamma_5 V_i B)_d$$

$$+ (1-\alpha)(\bar{B}\gamma_\mu\gamma_5 V_i B)_f] \mathcal{D}^\mu_\xi .$$

Here $g_A \simeq 1.25$ is the axial-vector current renormalization constant, m_o is an averaged baryon mass (2.26 GeV for charmed and 0.94 GeV for strange baryons, respectively), $\alpha = 2/3$ is the mixing parameter of d and f couplings defined by

$$(\bar{B}V_i B)_{d(f)} = \frac{1}{2} \bar{B}^a_{[mn]} (V_i)^b_a B_b^{[mn]} +(-) B^m_{[bn]} (V_i)^b_a B^{[an]}_m ,$$

where $B_i^{[jk]}$ represent the baryon fields ($B_i^{[ik]}=0$). The covariant derivative of baryon tensor is given by

$$\bar{B}\gamma_\mu D^\mu B = B^a_{[mn]} i\gamma_\mu \partial^\mu B^{[mn]}_a - (\bar{B}\gamma_\mu V_i B)_f \, \Theta^\mu_i(\xi),$$

and

$$D^\mu \xi = -\frac{i}{2} \mathrm{Tr}\left[A_i \exp(-i\xi\cdot A)\, \partial^\mu \exp(i\xi\cdot A)\right],$$

$V_i = \lambda_i/2$, $A_i = \gamma_5\lambda_i/2$, $\xi_i = \phi_i/F_\pi$, ϕ_i - is meson field. Θ^μ_i being the Cartan form,

$$\Theta^\mu_i(\xi) = -\frac{i}{2} \mathrm{Tr}\left[V_i \exp(-i\xi\cdot A)\, \partial^\mu \exp(i\xi\cdot A)\right].$$

The weak interaction Lagrangian, $\mathcal{L}_W$, is chosen in current-current form with the universal Fermi constant, $G = 10^{-5}/M_N^2$, and strictly satisfies the following selected rules:

$|\Delta T| = \frac{1}{2}$, $|\Delta S| = 1$, $|\Delta C| = 0$ ("octet dominance") (1)

$|\Delta T| = |\Delta S| = |\Delta C| = 1$ ("20 - plet dominance") (2)

From ref.6 we have the following expressions for (1) and (2) rules

$$\mathcal{L}_W(1) = \frac{G}{\sqrt{2}}\left[(J^1_\mu - iJ^2_\mu)(J^4_\mu + iJ^5_\mu) - (J^3_\mu + \frac{1}{\sqrt{3}}J^8_\mu)(J^6_\mu + iJ^7_\mu) + \mathrm{h.c.}\right]$$

and[7]

$$\mathcal{L}_W(2) = \frac{G}{\sqrt{2}}\left[(J^1_\mu - iJ^2_\mu)(J^{13}_\mu - iJ^{14}_\mu) - (J^9_\mu - iJ^{10}_\mu)(J^6_\mu + iJ^7_\mu) + \mathrm{h.c.}\right],$$

where $\mathcal{L}_W$ is sum of $\mathcal{L}_W(1)$ and $\mathcal{L}_W(2)$. The currents are nonlinear realization of chiral symmetry $SU_4 \times SU_4$

$$J^i_\mu = -F_\pi \partial_\mu \phi^i + f^i_{jk} \phi^j \partial_\mu \phi^k +$$

$$\frac{1}{2} \bar{B}^a_{[mn]} (V_i)^b_a \gamma_\mu B^{[mn]}_b - \bar{B}^m_{[bn]} (V_i)^b_a \gamma_\mu B^{[an]}_m +$$

$$g_A\left[\alpha(\bar{B}V^i\gamma_\mu\gamma_5 B)_d + (1-\alpha)(\bar{B}V^i\gamma_\mu\gamma_5 B)_f\right] + \dots$$

The next Lagrangian, $\mathcal{L}^{BB}_W$, corresponds to the baryon-baryon transitions that lead to baryon -pole contributions. We shall construct it phenomenologically on the basis of the rules (1) and (2), CP - invariance of weak interactions. Let us consider the fundamental representation of SU_3. Then, only one form, $X_{\alpha\beta}$, exists that transforms as octet under SU_3 transformations, it is

$$X_{\alpha\beta} = \{\lambda_1 + i\lambda_2, \lambda_4 - i\lambda_5\}_{\alpha\beta} - \{\lambda_3 + \frac{1}{\sqrt{3}}\lambda_8, \lambda_6 + i\lambda_7\}_{\alpha\beta},$$

where $\sum_{\alpha=1}^{3} X_{\alpha\alpha} = 0$. Using the commutation relations for the matrices λ_i the form $X_{\alpha\beta}$ may by presented as $(\lambda_6)_{\alpha\beta}$. Then, we have

$$\mathcal{L}^{BB}_W(1) = D_W \mathrm{Tr}(\{\bar{B}, B\}\lambda_6) + F_W \mathrm{Tr}([\bar{B}, B]\lambda_6),$$

where D_W and F_W are phenomenological (D- and F- coupling) parameters which are to be fixed from experiment, B is the field of the octet of $\frac{1}{2}^+$ baryons. In a similar way we construct the (2). In the fundamental representation of SU_4 there is only one tensor, $T^{[ij]}_{[kl]}$, that transforms as 20- plet

$$T^{[ij]}_{[k\ell]} = (\lambda_1 + i\lambda_2)^{[i}_{[k} (\lambda_{13} + i\lambda_{14})^{j]}_{\ell]} - (\lambda_9 + i\lambda_{10})^{[i}_{[k} (\lambda_6 - i\lambda_7)^{j]}_{\ell]} + h.c.,$$

where $\sum_{i=1}^{4} T^{[ij]}_{[i\ell]} = 0$. Using the Jakobi identity

$$B_{i[jk]} + B_{j[ki]} + B_{k[ij]} = 0,$$

where $B^{[jk]}_i = \frac{1}{2} \varepsilon^{jklm} B_{i[lm]}$, and physical components of baryon fields we finally have

$$\mathcal{L}^{BB}_w(2) = G^{BB}_w \Big[\frac{3}{\sqrt{6}} (\bar{\Xi}^0 \Lambda^0 - \bar{\Lambda}^0 \Sigma^0_c) + \frac{1}{\sqrt{6}} (\bar{\Sigma}^+ \Lambda^+_c + 2\bar{\Lambda}^+ X^+_d)$$
$$- \frac{1}{\sqrt{2}} (\bar{\Xi}^0 S^0 + \bar{\Sigma}^0 \Sigma^0_c - \Sigma^+ \Sigma^+_c) + h.c. \Big].$$

Here G^{BB}_w is a phenomenological parameter again.

III. Amplitudes

The two-body nonleptonic baryon decay amplitudes may be written in the following general form [11]

$$M_{i \to f} = G_J M^2 \bar{u}_f (S + P\gamma_5) u_i,$$

where M is meson mass. The numbers S and P define parity-violating (p-wave) and parity-conserving (s - wave)amplitudes, respectively. Only the absolute values of S and P are physically observable.

Table I contains the theoretical and experimental decay amplitudes of strange baryons. It is easy to test that the amplitudes satisfy the triangle and Lee-Sugawara relations [2]

$$M_{\Xi^- \to \Lambda^0 \pi^-} / M_{\Xi^0 \to \Lambda^0 \pi^0} = - M_{\Lambda^0 \to p\pi^-} / M_{\Lambda^0 \to n\pi^0} = \sqrt{2}$$

$$M_{\Sigma^+ \to n\pi^+} - M_{\Sigma^- \to n\pi^-} = \sqrt{2}\, M_{\Sigma^+ \to p\pi^0}$$

$$2M_{\Xi^- \to \Lambda^0 \pi^-} - M_{\Lambda^0 \to p\pi^-} = - \sqrt{3}\, M_{\Sigma^+ \to p\pi^0}.$$

Table I. The calculated and experimental [1] values of S and P for strange baryons when $F_w/D_w = 1$, and $F_w = -4{,}45 \times 10^{-8}$ GeV. The contributions from the diagrams shown in the fig. are denoted by A,B,C.

Type of decay	s - wave amplitude		p - wave amplitude				
	$S=S_A$	S_{exp}	P_A	P_B	P_C	$P=P_A+P_B+P_C$	P_{exp}
$\Lambda^0 \to p\pi^-$	-1,051	-1,47 ± 0,01	8,455	0,496	1,161	10,112	9,98 ± 0,24
$\Lambda^0 \to n\pi^0$	0,738	1,07 ± 0,01	-5,982	-0,351	-0,916	- 7,249	-7,14 ± 0,56
$\Sigma^+ \to p\pi^0$	0,859	1,48 ± 0,05	3,034	0,172	7,210	10,416	12,04 ± 0,58
$\Sigma^+ \to n\pi^+$	0	0,06 ± 0,01	0	0	19,391	19,391	19,07 ± 0,07
$\Sigma^- \to n\pi^-$	-1,247	-1,93 ± 0,01	-4,309	-0,243	0,427	- 4,125	-0,65 ± 0,07
$\Xi^0 \to \Lambda^0\pi^0$	-0,835	-1,54 ± 0,03	1,415	0,099	-7,417	- 5,903	-6,43 ± 0,66
$\Xi^- \to \Lambda^0\pi^-$	-1,219	-2,04 ± 0,01	2,006	0,070	-10,489	- 8,413	-6,93 ± 0,31

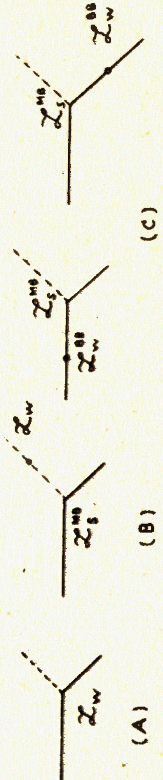

Figure. The diagrams of the nonleptonic weak decays of baryons in the "tree" approximation.

The signs of the experimental values of S and P ($S_{exp.}$ and $P_{exp.}$) in Table I are chosen in accordance with these relations. The numerical values of S and P correspond to fixations

$$F/D = 1 \text{ (ref.3)} \quad \text{and} \quad F_w = -4.45 \cdot 10^{-8} \text{ GeV}.$$

We note that the value of F_w in fact coincides with the symmetry breaking parameter,

$G \mu_\pi^4 / F_\pi = 4.6 \quad 10^{-8}$ GeV, in first order in F_π^{-1} expansion.

In Table II there are listed two-body nonleptonic decay amplitudes of light charmed baryons $\Lambda_c^+, A^+, A^\circ, T^\circ$, and their partial widths calculated when $G_w^{BB} = F_w^{BB}$.

IV. Discussion of the results.

The PCLM has been applied to the calculation of the nonleptonic decays of the charmed and strange baryons. The baryon-baryon transitions have been specified phenomenologically by one parameter which may by interpreted as the chiral symmetry breaking one in the corresponding order in F_π^{-1} expansion. By the nonleptonic decays of the strange baryons we have demonstrated that our results agree with the experimental data, with the exception of $\Sigma^- \to n\pi^-$, within the accuracy of PCLM. The latter is defined as the square of the Goldstone and baryon mass ratio, $(m_K / M_N)^2 \sim$ (20-30)% and $(m_F/M_\circ)^2 \sim$ (40-50)% for the strange and charmed baryons, respectively. The discrepancy of the calculated and measured values of the Σ^- decay amplitudes is most likely due to the fact that we have not taken into account the resonance pole contributions/4/. We neglected also the chiral symmetry breaking effects/6-8/

We have only two experimental values for nonleptonic decays of the charmed baryons, that is/1/

$$\Gamma(\Lambda_c^+ \to p\bar{K}^\circ) = (1.0^{+.68}_{-.78}) \cdot 10^{11} s^{-1}$$

$$\Gamma(\Lambda_c^+ \to \Lambda^\circ \pi^+) = (0.54 \pm 0.5) \cdot 10^{11} s^{-1}.$$

Our results (see TableII) are twice as large as the experimental values and are in agreement when their ratio is compared. We hope that taking into account the pole contributions from resonances by "hard" pion method/12/ one may describe more accurately the nonleptonic decays of the baryons.

Table II. The values of S and P , partial widths for the nonleptonic decays of ($\Lambda_c^+, A^+, A^\circ$ and T°) when $G_w^{BB} = F_w$. In calculations are used the following values of baryon masses: $M_{\Lambda_c^+} = 2.273$ GeV/1/, $M_{A^+} = 2.460$ GeV/13/, ($M_{A^\circ} = 2,476$ GeV, $M_{T^\circ} = 2.791$ GeV, $M_{\Sigma_c^\circ} = 2.452$ GeV, $M_{S^\circ} = 2.629$ GeV, $M_{\Sigma_c^+} = 2.439$ GeV)/8/

Type of decay	s - wave amplitude $S=S_A$	p - wave amplitude				Γ $\times 10^{11} s^{-1}$
		P_A	P_B	P_C	$P=P_A+P_B+P_C$	
$\Lambda_c^+ \to \Lambda^\circ \pi^+$	-5,604	11,382	0,084	-6,084	5,382	2,098
$A^+ \to \Xi^\circ \pi^+$	6,791	-15,548	-0,103	0,553	-15,098	4,355
$A^\circ \to \Xi^- \pi^+$	6,848	-15,640	-0,103	3,033	-12,710	4,047
$\Lambda_c^+ \to \Sigma^\circ \pi^+$	0	0	0	-1,106	- 1,106	0,007
$\Lambda_c^+ \to \Sigma^+ \pi^\circ$	0	0	0	1,218	1,218	0,007
$A^\circ \to \Xi^\circ \pi^\circ$	0	0	0	1,729	1,729	0,016
$\Lambda_c^+ \to \Sigma^+ \eta$	0	0	0	-0,078	-0,078	0,005
$A^\circ \to \Xi^\circ \eta$	0	0	0	0,330	0,330	0,109
$\Lambda_c^+ \to p \bar{K}^\circ$	-0,205	1,442	0,183	-0,085	1,540	3,460
$A^+ \to \Sigma^+ \bar{K}^\circ$	-0,196	1,639	0,183	0,178	2,0	4,315
$A^\circ \to \Sigma^\circ \bar{K}^\circ$	0,140	-1,165	-0,148	0,197	-1,116	1,446
$A^\circ \to \Lambda^\circ \bar{K}^\circ$	0,085	-0,658	-0,189	-0,609	-1,456	2,635
$T^\circ \to \Xi^\circ \bar{K}^\circ$	-0,557	-0,646	-0,064	-0,761	-1,471	6,190
$\Lambda_c^+ \to \Xi^\circ K^+$	0	0	0	-0,332	-0,332	0,046
$A^\circ \to \Sigma^+ K^-$	0	0	0	-0,657	-0,657	0,427

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Метод феноменологических киральных лагранжианов и нелептонные распады странных и очарованных барионов

Метод феноменологических киральных лагранжианов применяется для описания двухчастичных нелептонных слабых распадов и очарованных барионов. Построены феноменологические киральные лагранжианы, строго удовлетворяющие правилам отбора октетной и двадцатиплетной доминантности. Вычислены амплитуды распадов и проведено сравнение результатов с экспериментальными данными.

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