

$\Delta S=1$ Weak Transitions in Skyrme model Generalized up to Quartic Terms

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ABSTRACT

We investigate $\Delta S=1$ weak transition in the light of most general Skyrme type lagrangian containing terms up to quartic terms in field gradients. The additional parameters in the lagrangian are taken from pion-pion scattering data. Our decay amplitudes for anticommutator term in the Skyrme lagrangian shows much improvement over the Skyrme values. S-wave decay amplitudes are also reasonably reproduced in the model.

Keywords : Chiral Symmetry, Skyrmion, Heavier Mesons

I. INTRODUCTION

In Skyrme model, baryons emerge as solitonic solutions of non-linear pion field¹. ANW² calculated the physical properties of nucleons in the model within 30% accuracy. Since then, there has been motivation for studying mass spectrum and baryon static properties by including

- 1) mesons heavier than pion³⁻¹⁰
- 2) terms higher order in field derivatives¹¹⁻¹⁴ in the lagrangian. The extension of the model to strange sector to account for the large strange quark mass has been done by including chiral symmetry breaking terms whose complete survey is given in ref.¹⁵. If the Skyrme model has to emerge as an effective theory in the low limit, it must predict weak decays because as quoted by Scoccola¹⁶ these decays have been the least understood aspect of low energy weak interactions.

PT¹⁷ calculated the weak decay amplitudes of hyperons in Skyrme model by constructing a weak Hamiltonian in form of current-current interaction and using the baryon wave functions of the model. In these calculations $\Delta I=1/2$ rule (octet dominance) is

well satisfied. These decay amplitudes were compared with quark model (QM) values e.g. for transition

$$\Sigma^+ \rightarrow P + \pi^0$$

Skyrme model decay amplitude for a chirally symmetric lagrangian is

$$A = 0.65 \times 10^{-3} \text{ GeV}^3 \quad (1)$$

While for broken chiral symmetry, this amplitude is

$$A = 0.3 \times 10^{-3} \text{ GeV}^3 \quad (2)$$

The QM¹⁸ value for same transition is

$$A = 3.15 \times 10^{-3} \text{ GeV}^3 \quad (3)$$

It can be seen that chirally symmetric case(Eq.1) value is about five times smaller than QM value(Eq.3) and broken chiral symmetry(Eq.2) is about ten times smaller. It seems that

the origin of failure in reproducing the absolute weak decay amplitudes lies in the small values F_π (pion decay constant) which was used to predict the hyperon spectra¹⁹⁻²⁰. A similar study was carried out by Kondo et.al.²¹ with bound state approach to strangeness in the model. The results obtained were qualitatively similar to those obtained by PT¹⁷ but quantitatively different. PT¹⁷ quoted that lagrangian chosen

by them is the least part of the physical one. Therefore, in this paper, the aim is to investigate the non-leptonic weak decay amplitudes of hyperons in Skyrme model

by considering a generalized lagrangian up to quartic terms in field gradients.

Such a most general Skyrme type lagrangian was proposed

by Weinberg²². One term of this lagrangian i.e. $[Tr(\partial^\mu U \partial_\mu U^\dagger)]^2$

was considered by Lacombe et.al.²³ in the Skyrme model

for studying NN interaction and found that this term produces significant attraction in the intermediate range. It is, imperative, now to investigate the effects of additional terms proposed by Weinberg in the lagrangian on weak non-leptonic hyperon decay amplitudes. The paper is organized as follows

- In section 2, SU(3) Skyrme model is discussed by considering the most general Skyrme type lagrangian. For calculating the various integrals, arctan ansatz is used for chiral angle.
- Noether currents are discussed in section 3
- In section 4, current×current weak Hamiltonian is derived in terms of SU(3) D-functions.
- Section 5 concludes the paper.

2. SU(3) Skyrme Model

The Skyrme lagrangian density⁷ is

$$\mathcal{L}_{sk} = \frac{f_\pi^2}{4} \text{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{1}{32e^2} \text{Tr} [\partial_\mu U U^\dagger, \partial_\nu U U^\dagger]^2 \quad (4)$$

$f_\pi = \frac{f_\pi}{2}$ is pion decay constant.

Weinberg proposed that most general Skyrme type lagrangian density up to quartic in field derivatives is given by

$$\mathcal{L}_w = \mathcal{L}_{sk} + \frac{\beta}{32e^2} \text{Tr}[\partial_\mu U U^\dagger, \partial_\nu U U^\dagger]_+^2 + \frac{\gamma}{8e^2} [Tr(\partial_\mu U^\dagger \partial^\mu U)]^2 \quad (5)$$

β and γ are taken from π - π scattering data. Effective lagrangian is chosen as

$$L = \int \mathcal{L} d^3r + N_c \Gamma \quad (6)$$

where

$$\mathcal{L} = \mathcal{L}_w + \frac{f_\pi^2}{8} (m_\pi^2 + m_\eta^2) \text{Tr}(U + U^\dagger - 2) + \frac{\sqrt{3}}{6} f_\pi^2 (m_\pi^2 - m_K^2) \text{Tr} \lambda_8 (U + U^\dagger) \quad (7)$$

$$\Gamma = -\frac{i}{240 \pi^2} \int d\Sigma^{\mu\nu\rho\sigma} \text{Tr}(\partial_\mu U U^\dagger \partial_\nu U U^\dagger \partial_\rho U U^\dagger \partial_\sigma U U^\dagger) \quad (8)$$

The lagrangian (Eq.6) has the static solution

$$U_0(r) = \exp(\lambda_j \frac{r^j}{r} F(r)) \quad (9)$$

The model is quantized by making the unitary transformation

$$U(r, t) = A(t) U_0(r) A^{-1}(t) \quad (10)$$

where A(t) is time dependent SU(3) matrix which defines general velocities a

$$A^{-1} \dot{A} = \frac{1}{2} i \sum_{a=1}^8 \lambda_a \dot{a}_a \quad (11)$$

λ_a are the Gell- Mann SU (3) matrices. The chiral angle F(r) is subjected to boundary conditions The lagrangian (Eq.5) is, now, transformed to

$$L = -M + \frac{1}{2} I_1 \sum_{i=1}^3 \dot{a}^2 + \frac{1}{2} I_2 \sum_{j=4}^7 \dot{a}^2 + \frac{N}{2\sqrt{3}} \dot{a}_8 + \frac{1}{2} Y_m D_{88} \quad (13)$$

where M is the classical soliton mass. The quantities I_1 and I_2 represent the moment of inertia for rotations in co-ordinate space and flavor rotations in the directions of strangeness respectively with

$$M = 2\pi \frac{f_\pi}{e} \int x^2 dx [(F'^2 + \frac{\sin^2 F}{x^2}) + \frac{\sin^2 F}{x^2} (2F'^2 + \frac{\sin^2 F}{x^2}) - \frac{\beta}{2} (F'^4 + 2 \frac{\sin^4 F}{x^2}) - \gamma (F'^2 + 2 \frac{\sin^2 F}{x^2}) + \mu^2 (1 - \cos F)] \quad (14)$$

$$I_1 = \frac{8\pi}{3} \frac{1}{e^3 f_\pi} \int x^2 \sin^2 F [1 + (F'^2 + \frac{\sin^2 F}{x^2}) - \beta \frac{\sin^2 F}{x^2} - 2\gamma (F'^2 + 2 \frac{\sin^2 F}{x^2})] dx \quad (15)$$

$$I_2 = \frac{\pi}{2e^3 f_\pi} \int x^2 (1 - \cos F) [4 + \{1 - (\beta + 8\gamma)\} (F'^2 + 2 \frac{\sin^2 F}{x^2})] dx \quad (16)$$

$$Y_m = \frac{16\pi}{3} (m_K^2 - m_\pi^2) \frac{1}{e^3 f_\pi} \int x^2 (1 - \cos F) dx \quad (17)$$

$$\text{where } x = e f_\pi r \quad (18)$$

$$\mu = \frac{1}{e f_\pi} (m_\pi^2 + m_\eta^2) \quad (19)$$

$$\text{and } D_{88} = \frac{1}{2} \text{Tr} (\lambda_8 A^\dagger \lambda_8 A) \quad (20)$$

Hamiltonian corresponding to Eqn. (13) is

$$H = M + \frac{1}{2} (\frac{1}{I_1} - \frac{1}{I_2}) J(J+1) + \frac{1}{2I_2} \{C_2[SU(3)] - \frac{3}{4}\} - \frac{1}{2} Y_m D_{88} \quad (21)$$

The chiral angle F(r) is taken in terms of arc-tan ansatz²⁸

$$F(r) = 2 \arctan \left[\left(\frac{r_0}{r} \right)^2 \right] \quad (22)$$

where r_0 (the soliton size) is the variational parameter and second power of $\frac{r_0}{r}$ is determined by long distance behavior of eqn. of motion. After rescaling $x = e f_\pi r$, $\frac{r_0}{r} = \frac{x_0}{x}$, where x_0 is the dimensionless size of soliton and is determined by minimizing the classical mass M (Eq.14). The Eq. (14-17) can, now, be easily evaluated in terms of x_0 by using Eq. (22) and gamma functions²⁹⁻³⁰. We find

$$M = k \frac{f_\pi}{e} \left[x_0 + \frac{15}{16} \frac{1}{x_0} - \beta \frac{21}{16} \frac{1}{x_0} - \gamma \frac{15}{4} \frac{1}{x_0} + \frac{\mu^2}{3} x_0^3 \right] \quad (23)$$

$$I_1 = \frac{2}{9} \frac{k}{e^3 f_\pi} \left[3x_0^2 + \frac{25}{8} - \frac{5}{8} \beta - \frac{15}{2} \gamma \right] x_0 \quad (24)$$

$$I_2 = \frac{2}{9} \frac{k}{e^3 f_\pi} \left[4x_0^2 + \frac{9}{4} \{1 - (\beta + 8\gamma)\} \right] x_0 \quad (25)$$

$$Y_m = \frac{8}{9} \frac{k}{e^3 f_\pi} (m_k^2 - m_\pi^2) x_0^3 \quad (26)$$

where $k = 3\sqrt{2} \pi^2$
 Minimising M (Eq.23) (27)

$$\mu^2 x_0^4 = \left(\frac{15}{16} - \frac{21}{16} \beta - \frac{15}{4} \gamma \right) - x_0^2 \quad (28)$$

From this eqn. one can find the soliton size x_0 in terms of β , γ and μ . Using this x_0 , the values of M, I_1, I_2 and Y_m can be obtained from Eqs.(23-26). From these values, baryon masses are determined¹⁹. We consider the two cases:

Case 1. Chirally symmetric limit ($m_\pi = m_k = 0, \mu = 0$)
 Here, the average octet and decuplet masses are fitted¹⁹ for predicting f_π and e in the following three sub-cases as:
 a) $\beta = \gamma = 0$ (Skyrme model)

one gets $x_0 = \frac{\sqrt{15}}{4}$ (29)

with $f_\pi = 52.46 \text{ MeV}, e = 5.4$ (30)

b) $\beta = 0, \gamma = 0.16^{31}$
 with these parameters, f_π comes out to be negative and hence is

is not considered. It happens due to small value of strange moment of inertia I_2 . For $\gamma = 0.09$, we find

$$x_0 = \sqrt{3/5} \quad (31)$$

$$f_\pi = 47.28 \text{ MeV}, e = 4.64 \quad (32)$$

c) $\beta = 0.44^{32}, \gamma = 0$
 These parameters yield

$$x_0 = \sqrt{3/4} \quad (33)$$

$$\text{and } f_\pi = 51.7 \text{ MeV}, e = 4.03 \quad (34)$$

Case 2. Broken chiral symmetry ($\beta = \gamma = 0$)
 $m_\pi = 139 \text{ MeV}, m_k = 495 \text{ MeV}$
 and $\mu^2 = 35$, we get

$$x_0 = 0.15 \quad (35)$$

$$\text{the masses } m_\Lambda \text{ and } m_{\Sigma^*} \text{ are fitted}^{19} \text{ which gives } f_\pi = 20.57 \text{ MeV}, e = 4.46 \quad (36)$$

The values obtained for x_0, f_π and e in cases 1 & 2 will be used in calculating the hyperon decay amplitudes in section 4.

3. Noether Currents

The left Noether currents in the model for lagrangian (Eq.6) can be easily obtained². These currents for different pieces of the lagrangian are

$$J_{\mu,a}^{L,sk} = i \frac{f_\pi^2}{2} \text{Tr}(\lambda_a \partial_\mu U U^\dagger) + \frac{i}{8e^2} \text{Tr}[\partial^\nu U U^\dagger, \lambda_a][\partial_\mu U U^\dagger, \partial_\nu U U^\dagger] \quad (37)$$

$$J_{\mu,a}^{L,\beta} = -\frac{i}{8e^2} \text{Tr}[\lambda_a, \partial^\nu U U^\dagger] + [\partial_\mu U U^\dagger, \partial_\nu U U^\dagger]_+ \quad (38)$$

$$J_{\mu,a}^{L,\gamma} = i \frac{\gamma}{2e^2} \text{Tr}(\partial^\nu U \partial_\nu U^\dagger) (\text{Tr} \lambda_a \partial_\mu U U^\dagger) \quad (39)$$

$$J_{\mu,a}^{L,WZ} = -\frac{N_c}{48\pi^2} \epsilon_{\mu\nu\alpha\beta} \text{Tr} \lambda_a (\partial_\nu U U^\dagger) (\partial_\alpha U U^\dagger) \partial_\beta U U^\dagger \quad (40)$$

Like in ref.¹⁷ only static contributions of currents are taken in account. Terms proportional to \dot{a} and \dot{a}^2 are neglected.

4. Weak Interaction Hamiltonian

The current-current weak interaction Hamiltonian is given by¹⁶⁻¹⁷

$$H_W^{eff} (\Delta S = 1) = \frac{G_F}{\sqrt{2}} \sin \theta_c \cos \theta_c J_{L\rho}^{(1-i2)} J_\rho^{(4+i5)} + \text{h.c} \quad (41)$$

Consider the operator $\hat{O}(\Delta S = 1) = J_{Lj}^{1-i2} J_{Lj}^{4+i5}$ (42)

By using the ansatz (Eq.10), Noether currents (sec 3), arc tan ansatz (Eq.22) and by evaluating the space integral with the help of gamma functions, we get^{16,33}

$$\hat{O}(\Delta S = 1) = -\varphi R_{\pi-a} R_{K^+a} \quad (43)$$

where
$$\varphi = k \frac{f_\pi^3}{e} \left\{ 2 x_0 + \frac{15}{2x_0} [1 - (\beta + 4\gamma)] + \frac{1}{x_0^3} \left[\frac{847}{164} (1 + \beta^2) + \frac{693}{8} \gamma (2\gamma - 1) - \beta \frac{1078}{64} \right] \right\} \quad (44)$$

$$R_{\pi-a} R_{K^+a} = -\frac{3\sqrt{6}}{5} D_{\frac{1}{2},0}^8 - \frac{1}{10} D_{\frac{1}{2},0}^{27} - \frac{1}{\sqrt{20}} D_{\frac{3}{2},0}^{27} \quad (45)$$

here the left lower index of SU (3) D function $I = \frac{1}{2}, \frac{3}{2}$ stands for $(YI)_3 = (11-\frac{1}{2})$ and right lower index for (000).

The hyperon decay amplitudes can be obtained by evaluating the matrix elements of $\hat{O}(\Delta S = 1)$ (Eq. 43) between different hadronic states or wave functions³⁴⁻³⁵ in the model i.e.

$$\langle B_f | \hat{O}(\Delta S = 1) | B_i \rangle$$

with the help of SU (3) C.G. coefficients³⁶. These matrix elements are also given in ref.³⁷ (table II, matrix elements of operator T_0).

Both symmetric and antisymmetric octet contribute to the matrix elements. In the transitions $B_i \rightarrow B_f$ octet dominance is exhibited because C.G. coefficients for $8 \times 8 \rightarrow 27$ and $8 \times 27 \rightarrow 8$ are smaller in magnitude than those for $8 \times 8 \rightarrow 8$ e.g

$$\langle P | \hat{O}(\Delta S = 1) | \Sigma^+ \rangle = [(20.00)_8 + (0.37)_{27}] \varphi \times 10^{-3} \quad (46)$$

Our values of transition magnitudes relative to $\varphi \times 10^{-3}$ agree with those of ref.³⁸ (table II a) and are given, here, in table 1 for easy reference. The relative values of matrix elements are given in table 2. There is a sign difference, here, for transitions $\Sigma^0 \rightarrow N$ and $\Xi^0 \rightarrow \Lambda^0$ and $\Lambda^0 \rightarrow N$ w.r.t those in ref.¹⁷. To check it, we calculate the amplitude $A(\Sigma^+)$ which in QM is zero. This amplitude is given by¹⁶

$$A(\Sigma^+) = -\frac{1}{\sqrt{2}} f_\pi^{-1} [\langle P | H_W^{eff} (\Delta S = 1) | \Sigma^+ \rangle + \sqrt{2} \langle N | H_W^{eff} (\Delta S = 1) | \Sigma^0 \rangle] \tag{47}$$

which yields zero by using the respective matrix elements from table 1 verifying the QM result.

Now, we embark on hyperon decay amplitudes. For it, first the amplitude of transition $\Sigma^+ \rightarrow P$ is evaluated from Eq.(46). Then, other amplitudes can be found by using table 2. Following two cases are taken

Case 1. Chiral symmetric limit i.e.

$$m_\pi = m_k = 0$$

Depending on β and Y , there are three sub-cases

a) $\beta = Y = 0$ (Skyrme model)

By using the soliton size x_0 (Eq. 29), f_π & e (Eq. 30) in Eq. (44), φ is calculated which when used in Eq.(46) gives for octet dominance, the amplitude

$$A(\Sigma_0^+) = 0.55 \times 10^{-3} GeV^3 \tag{48}$$

which is about same as the Skyrme value (Eq.1) obtained numerically.

b) $Y \neq 0$, $\beta = 0$

For $Y = 0.09$, by following on lines of sub-case a, we get

$$A(\Sigma_0^+) = 0.04 \times 10^{-3} GeV^3 \tag{49}$$

which is less than the corresponding Skyrme value (eqn.1).

It means Y term taken in the lagrangian does not improve the decay amplitudes.

c) $\beta \neq 0$, $Y = 0$

Here $\beta = 0.44$, we obtain on the same lines as above

$$A(\Sigma_0^+) = 1.35 \times 10^{-3} GeV^3 \tag{50}$$

which is twice the Skyrme value (Eq.1). Therefore, β term taken in the lagrangian produces a major change in decay amplitudes in positive direction. It was the main aim of paper to check. But the value obtained here is still less than the QM value (Eq.3).

Case 2. Broken chiral symmetry

$$m_\pi = 139 MeV, m_k = 495 MeV$$

With the parameters of Eq. (35&36), one obtains

$$A(\Sigma_0^+) = 0.4 \times 10^{-3} GeV^3 \tag{51}$$

This value shows some improvement over the Skyrme value (Eq.2).

To further check the effectiveness of β term in the lagrangian, we calculate also the S-wave non-leptonic hyperon decay amplitudes by following the approach of ref.³⁹ where f_π is kept at its experimental value and $e=4.1$ (a suitable set of parameters for the description of baryon properties). The effective phenomenological constants take into account all QCD enhancement factors embodied into the constants C_i . With $C_1 = 2.75$ ⁴⁰ and effective hamiltonian (Eq.41), The S-wave decay amplitudes for transition $\Sigma^+ \rightarrow P + \pi^0$ corresponding to β term in the lagrangian is

$$A(\Sigma_0^+) = -3.11 \times 10^{-7} \tag{52}$$

where $f_\pi = 93 MeV$ and $e = 4.03$ which is close to 4.1.

Our values for $A(\Sigma_0^+)$ is greater in magnitude than corresponding value for parameters Set A³⁷ and is nearly equal to QM⁴¹ value. The other results for the amplitudes are summarized in table 3, where the corresponding QM values are also given. The P-wave decay amplitudes has contributions from the contact and pole terms. But the simultaneous description of both S- and P- wave decay amplitudes is not possible in the models based on chiral symmetry⁴². The S wave/ P wave amplitudes in the model will be addressed separately for the lagrangian $\beta \neq 0$ and $\gamma = 0$.

II. CONCLUSION

We have studied $\Delta S=1$ weak transition amplitudes in the Skyrme model generalized up to quartic terms in field gradients. The analysis shows that a) the term $\gamma \neq 0$, $\beta = 0$ does not show any improvement in decay amplitudes b) $\beta \neq 0$ and $\gamma = 0$ term

shows major improvement in decay amplitudes over Skyrme values, still less than QM values. S-wave non-leptonic hyperon decay amplitudes calculated for β term agree quiet well with QM values but less than experimental values.

Table 1. Relative values of baryon matrix elements

$$\langle B_f | \hat{O} (\Delta S = 1) | B_i \rangle$$

The relative phases are so chosen that $-\Sigma^+$ and $-\Xi^-$ are used in 3×3 octet matrix elements

$\langle B_f \hat{O} B_i \rangle / (\varphi \times 10^{-3})$	$8(8_d + 8_f)$	$27(\Delta I = \frac{1}{2})$	$27(\Delta I = \frac{3}{2})$
$P \Sigma^+$	20.00	0.06	0.31
$N \Sigma^0$	$-20.00/\sqrt{2}$	$-0.06/\sqrt{2}$	$0.31/\sqrt{2}$
$\Lambda \Xi^0$	-18.38	0.23	0.00
$N \Lambda$	12.25	0.23	0.00
$\Sigma^- \Xi^-$	-5.00	0.06	0.31
$\Sigma^0 \Xi^0$	$5.00/\sqrt{2}$	-0.06	$0.31/\sqrt{2}$

Table 2. Relative value of $\langle B_f | \hat{O} (\Delta S = 1) | B_i \rangle$ compared with quark model result.

$\langle B_f \hat{O} (\Delta S = 1) B_i \rangle$	Skyrme Model 8 Contribution	Quark Model 8 Contribution
$P \Sigma^+$	1.00	1.00
$N \Sigma^0$	-0.71	-0.71
$\Lambda^0 \Xi^0$	-0.91	-0.81
$N \Lambda^0$	0.61	0.41
$\Sigma^- \Xi^-$	-0.25	0.00
$\Sigma^0 \Xi^0$	0.18	0.00

Table 3. S-wave non-leptonic hyperon decay amplitudes compared with QM and experimental values. All values are multiplied by 10^{-7} .

Transition $B_i \rightarrow B_f$	Our values	Quark Model [QM] values	Experimental Values
$\Sigma^+ \rightarrow P(\Sigma_0^+)$	-3.11	-3.8	-3.28
$\Lambda^0 \rightarrow N(\Lambda_0^0)$	-1.90	-1.5	-2.37
$\Sigma^+ \rightarrow N(\Sigma_0^+)$	0	0	0.13
$\Xi^0 \rightarrow \Lambda^0(\Xi_0^0)$	2.86	3.0	3.43

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