Roles of quark-pair correlations in baryon structure and non-leptonic weak transitions of hyperon

K. Suzuki[a], E. Hiyama[b], H. Toki[a], M. Kamimura[c]

[a] *RCNP, Osaka University, Osaka 567-0047, Japan*
[b] *RIKEN, Saitama 351-0198, Japan*
[c] *Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*

Properties of light baryons have been extensively studied based on the constituent quark picture, in which the constituent quarks are assumed to be identified with quasi-particles of QCD vacuum. Their results including applications for the two nucleon system are consistent with experiments. Despite the success of this approach, understandings of the non-leptonic weak hyperon decay and its $\Delta I = 1/2$ rule are still incomplete[1, 2].

It is well known that the factorization as well as the penguin contributions are too small to reproduce the $\Delta I = 1/2$ rule. Making use of the soft pion theorem, one can derive the baryon pole contribution to the non-leptonic decay, where initial hyperon B_i first changes to the intermediate state baryon B_l by the weak interaction and then B_n emits the pion to produce the final state B_f(and vice versa). The pole approximation with the SU(6) spin-flavor symmetry can reproduce relative magnitudes of various hyperon decays very well. However, if one calculates these transition amplitudes using the constituent quark model, the absolute value of the amplitudes is about a half of the experimental data at most[2].

Our task here is to evaluate the strangeness changing matrix element $\langle B_f \pi^a | \mathcal{H}_W | B_i \rangle$, where $\mathcal{H}_W$ is the well-known low energy effective weak Hamiltonian[1]. It can be shown that these decay amplitudes are essentially determined by the matrix elements of the weak Hamiltonian between the intermediate baryon states, which are given by

$$\langle B_i | O_1, O_2 | B_j \rangle \rightarrow \langle B_i | \, a_d^\dagger \, a_u^\dagger \, (1 - \vec{\sigma}_u \cdot \vec{\sigma}_s) \, a_u a_s \, \delta^{(3)}(\vec{r}_{us}) \, | B_j \rangle \tag{1}$$

where a_i, $a_i^\dagger$ are annihilation and creation operators of quarks with flavor i. Presence of the spin-projection operator $(1 - \vec{\sigma}_u \cdot \vec{\sigma}_s)$ tells us that only the us pair with their total spin s being 0 can contribute to the weak decay process, namely, the weak transition is generated by the two body process between spin-0 quark pairs; $(us)^0 \rightarrow (ud)^0$. It is clear that this decay amplitude is very sensitive to the correlation between quarks with $s = 0$ in the baryons. The standard constituent quark model never incorporates such a correlation properly, and thus cannot reproduce the $\Delta I = 1/2$ amplitudes. However, in fact, existence of the attractive strong correlation in the $s = 0$ channel is suggested from both theoretical and phenomenological points of view. We shall clarify the roles of quark-pair correlations in the baryon structure and the non-leptonic weak transitions using the non-relativistic constituent quark model[3].

We phenomenologically introduce the non-relativistic effective Hamiltonian which includes the confinement force and the spin-dependent part as;

$$\mathcal{H} = \sum_i \frac{p_i^2}{2m_i} + V_{Conf} + V_S \tag{2}$$

$$V_S = \begin{cases} 0 \quad (s = 1 \text{ pair}) \\ \sum\limits_{i<j} \frac{C_{SS}}{m_i m_j} \mathrm{Exp}\left[-(\vec{r}_i - \vec{r}_j)^2 / \beta^2 \right] \quad (s = 0 \text{ pair}) \end{cases} \tag{3}$$

Using this Hamiltonian, we shall solve non-relativistic three body problem rigorously. We use the coupled-rearrangement-channel variational method with infinitesimally-shifted-Gaussian-

Lobe basis functions, developed by E.H. and M.K. We assume only the isospin symmetry between up and down quarks. The quark wave functions are constructed by the antisymmetrization without any further approximations or assumptions. Note that the SU(6) spin-flavor symmetry should be broken within our formalism because of the spin-dependent correlation.

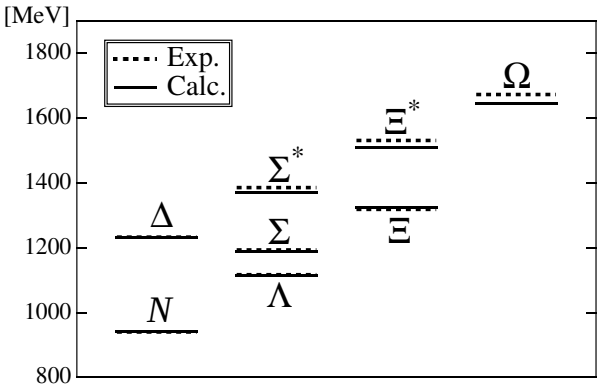

Figure 1: SU(3) baryon mass spectrum

We shall fix the model parameters so as to reproduce the nucleon and Δ masses, radius$\simeq$ 0.6fm and strength of the non-leptonic hyperon decay. We show first in Fig.1 SU(3) baryon mass spectrum. The agreement with the data encourages us to proceed our approach.

The weak matrix elements are shown in Table 1. In the absence of the correlation $C_{SS} = 0$, a ratio $\langle p|H_W|\Sigma^+\rangle/\langle n|H_W|\Lambda\rangle = -2.45$ shows a perfect agreement with the SU(6) expectation $\sqrt{6} \simeq -2.4494\cdots$. In the realistic case with the spin-dependent force, one can see the substantial enhancement of the matrix elements and the SU(6) breaking effects. The non-leptonic weak transition amplitudes are tabulated in table 2. We shown the pole contributions only in the second column and the total decay amplitudes with the factorization and penguin contributions together in the third column. We find a good agreement for $\Sigma \to N\pi$ decays. The pole contribution for $\Lambda \to n\pi^0$ is small and thus the total amplitude becomes about a half of the data. This is because the SU(6) breaking effect on our quark wave function tends to reduce the matrix element $\langle n|H_W|\Lambda\rangle$ relatively. It is very important to note that the magnetic moments of the baryons calculated by the model are almost unchanged compared with the SU(6) limit case, even if there are strong correlations between quarks. This implies that the magnetic moments are quite insensitive to the modification of the local structure of the wave function driven by the short range correlation.

Table 1 Matrix elements of $\mathcal{H}_W$

	with V_S	without V_S
$\langle n\|\mathcal{H}_W\|\Lambda\rangle$	-0.546	-0.179
$\langle p\|\mathcal{H}_W\|\Sigma^+\rangle$	1.65	0.440

Table 2 P-wave transition amplitudes

Decay	Pole	total	Exp.
$\Sigma \to p\pi^0$	26.0	28.05	26.24 ± 1.32
$\Sigma^+ \to n\pi^+$	43.4	43.3	41.83 ± 0.17
$\Lambda \to n\pi^0$	-2.30	-7.32	-15.61 ± 1.40

References

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