We study the vacuum structure of the model in the case of $N_f = 2$ using the leading order Lagrangian, and show that the flavor-singlet "ω"-meson carrying $J^P = 1^-$ has a vacuum expectation value in the time component. As a result, the phase structure is the same as the one determined by including only the pseudo-NG bosons [3]: For $\mu_B > M_\pi$, a baryonic pseudo-NG boson ($J^P = 0^+$ state) condenses, which causes the spontaneous breaking of the baryon number symmetry, $U(1)_B$. We show that the mass of the anti-baryon (baryon) with $J^P = 1^+$ increases (decreases) for $\mu_B < M_\pi$ and turns to decrease (increase) for $\mu_B > M_\pi$. These behaviors signal the phase transition of $U(1)_B$ breaking. The effect of higher order terms is shown to make ρ and ω meson masses decrease for $\mu_B > M_\pi$ consistently with lattice data [6, 7]. Furthermore, the mass difference between ρ and ω mesons is proportional to the mixing strength between the diquark baryon with $J^P = 1^+$ and the anti-baryon.

The paper is organized as follows. In section 2 we construct the chiral Lagrangian based on the HLS. The vacuum structure and the μ_B-dependences of the masses are studied at the leading order in section 3. In section 4 we show the effects of higher order terms to the masses and mixings. Section 5 is devoted to a summary and discussions. Several intricate calculations and useful formulas are summarized in Appendices A-C.

2. HLS MODEL IN TWO-COLOR QCD

Let us construct a low energy effective Lagrangian including NG bosons associated with the spontaneous chiral symmetry breaking $SU(2N_f) \to Sp(2N_f)$, following Ref. [3].

In the following we divide the hermitian generators, $\{T^A\}$ of $SU(2N_f)$ normalized as $\mathrm{tr}[T^A T^B] = \delta^{AB}/2$, into two classes: The generators of $Sp(2N_f)$ denoted by $\{S^\alpha\}$ with $\alpha = 1, ..., 2N_f^2 + N_f$; and the remaining generators of $SU(2N_f)$ by $\{X^a\}$ with $a = 1, ..., 2N_f^2 - N_f - 1$. These generators satisfy the relations

$$(S^\alpha)^T = \bar{\Sigma} S^\alpha \bar{\Sigma}, \qquad (X^a)^T = -\bar{\Sigma} X^a \bar{\Sigma}, \tag{2.1}$$

where $\bar{\Sigma}$ is a $2N_f \times 2N_f$ matrix satisfying following properties:

$$\bar{\Sigma}^2 = -\mathbf{1}, \qquad \bar{\Sigma}^T = \bar{\Sigma}^\dagger = -\bar{\Sigma}. \tag{2.2}$$

The chiral symmetry breaking gives $2N_f^2 - N_f - 1$ NG bosons π which are encoded in the $2N_f \times 2N_f$ matrix as

$$\Sigma = \xi(\pi) \bar{\Sigma} \xi^T(\pi), \tag{2.3}$$