Baryon-Baryon Interaction in the Quark Cluster Model

Makoto OKA

Department of Physics, Tokyo Institute of Technology
Meguro, Tokyo 152-8551 Japan
Email:oka@th.phys.titech.ac.jp

The quark cluster model approach to the baryon-baryon interaction is reviewed and recent application to the charge symmetry breaking in nuclear force is discussed.

§1. Introduction

According to quantum chromodynamics (QCD), hadrons are bound states of quarks and gluons, and their interactions are governed by the non-Abelian gauge interaction. Their structures are potentially very complex as QCD is strongly interacting in the hadronic energy region. Indeed, we have many reasons to believe that the QCD vacuum (ground state) has nontrivial structure, such as chiral symmetry breaking, nontrivial topology. On the other hand, the low energy excitations of mesons and baryons show regular spectrum, which indicates their structures are rather simple. In terms of the Fock space decomposition, dominant component of a meson or a baryon seems to be simply $q\bar{q}$ or $qqq$.

Chiral symmetry breaking is a key to resolve this seemingly contradictory situation. That is, spontaneous chiral symmetry breaking induces a gap in the quark spectrum, so that the effective quark, called constituent quark, acquires a mass of order 300 MeV. As this mass gap reduces the mixing of higher Fock components, or mixing of extra $q\bar{q}$, the leading Fock component becomes dominant. This is the basis of the quark model, in which hadrons can be treated as few-body quantum systems and various techniques developed for few-body quantum systems may be applied.

One fruitful application of the quark model is the quark cluster model (QCM) approach to the baryon-baryon interactions. The QCM, originally developed for the nucleon-nucleon interaction, successfully explained the origin of the strong short-range repulsion\(^1\). Later it was applied to other baryons, such as the $\Delta$ resonance, and the hyperons, $\Lambda$, $\Sigma$, and $\Xi$. Short range parts of such baryon-baryon interactions, which had not been well studied experimentally, have been predicted. For instance, the $H$ dibaryon\(^2\) is predicted to be a bound state of $\Lambda\Lambda$ in QCM\(^3\) which motivated extensive dibaryon searches.

Realistic baryon-baryon interactions have been generated in using a hybrid picture, i.e., superposition of the short-range quark exchange interaction and the meson exchange potential at longer distance.\(^4\) Such hybrid models of nuclear force are very successful and furthermore they have enough predictive power on the other baryon-baryon interactions. Recent development of hypernuclear experiments have confirmed some of the characteristic features of the QCM based $\Lambda - N$ interactions.
In this short note, I would like to review the status of the QCM and describe a new result on the charge symmetry breaking in QCM.

§2. Status of the Quark Cluster Model

The quark cluster model (QCM) is designed to describe quark exchange interactions between baryons. The basic idea is that the quark antisymmetrization between two three-quark baryons induces symmetry interaction, which is either attractive for orbitally symmetric states, or repulsive for orbitally antisymmetric states. Such interaction has been well known in the hydrogen molecule as was pointed out by Heitler and London in 1927. It is the symmetry of internal quantum numbers, such as spin in the case of molecules, that determines the main features of the exchange force.

In the case of quark exchange interaction, the symmetry is controlled by three internal degrees of freedom, color, spin and flavor. Consider the symmetry group for the six quarks, \(S_6\) in the \(BB'\) states, where \(B\) and \(B'\) are the ground state baryons. The color part of the two-baryon state must have \([222]_c\) symmetry so that the whole system is color \(SU(3)_c\) singlet. As the ground state baryons belong to the 56-dimensional or \([3]\) symmetric representation of the spin-flavor \(SU(6)_{sf}\), two baryon system is classified by \([3] \otimes [3] = [6] \oplus [51] \oplus [42] \oplus [33]\) symmetric representations. Among them, \([6]_{sf}\) and \([42]_{sf}\) are symmetric under the exchange of two \([3]'s and [51]_{sf}\) and \([33]_{sf}\) are antisymmetric, and therefore \([51]_{sf}\) and \([33]_{sf}\) are relevant for \(L = 0\) \(BB'\) states. It is, however, easy to see that the \([51]_{sf}\) symmetric \(SU(6)_{sf}\) state cannot have the totally symmetric orbital wave function because the color \([222]_c\) and the spin-flavor \([51]_{sf}\) symmetries do not form the totally antisymmetric state: \([222]_c \times [51]_{sf} \times [6]_o \neq [16]\) Thus we find that the totally symmetric orbital state such as \((0s)^6\) is not allowed for the \([51]\) symmetric \(SU(6)_{sf}\) systems.

Thus the classification of the \(BB'\) states in terms of the \(SU(6)_{sf}\) representations tells us which \(BB'\) acquires strong repulsion at short distances. In the case of \(N\Sigma\) interactions, there are four possible combinations of spin and isospin. Among them, the \((S = 0, I = 1/2)\) and \((S = 1, I = 3/2)\) states should have strong repulsion at short distances, because their \(S\)-wave states are almost forbidden by the Pauli principle. On the contrary, the “H-dibaryon” channel, \((S = 0, I = 0)\) \(\Lambda\Lambda - N\Xi - \Sigma\Sigma\), contains only the \([33]\) component and therefore “super-allowed”. This is one of the reasons why “H-dibaryon” is expected to have a bound state. Another reason is that the “H” is preferred by the color-magnetic interaction.

In the case of \(NN\) interactions, the Pauli principle is not enough to reproduce the strong short-range repulsion, because the \(S\)-wave \(NN\) states consist of only 44% \([51]\) symmetry forbidden state. In our original study, we pointed out that the color-magnetic part of the gluon exchange interaction is responsible for the repulsion. Later it was found that the spin-spin (or hyperfine) interaction is the key, whose origin may have several possibilities. For instance, the instanton induced interaction or the pion exchange interaction may work as well as OgE. It is also known that the success of the quark model description of the meson and baryon spectra owes largely to the same spin-spin interaction between quarks. For instance, \(N - \Delta\) and \(\Lambda - \Sigma\) mass differences and the negative mean square charge radius of the neutron
are all explained by the spin-spin interaction. Strange baryons play important roles in confirming the origin of short-range interactions. They include new channels with different internal symmetry from \(NN\). Also the \(SU(3)\) breaking pattern gives further information.

The present status of the QCM can be summarized as follows.

1. Nuclear force: QCM with meson exchange potential supplemented for long range interaction describes \(NN\) interaction pretty well. Main difference among the models appear in the treatment of smooth connection between the short and long range parts. A natural way is to introduce a form factors that the short-range part of the meson-exchange potential is reduced according to the extension of the baryons, which is about 0.6 fm. Some disagreement still exists on the origin of the spin-orbit forces among the models.

2. \(YN\) interaction: The spin independent part of the central force agrees among the models and with experiment fairly well, while the spin-spin and spin-orbit interactions differ. The QCM predicts strong antisymmetric \(LS\) force between \(Λ\) and \(N\) which is a strong candidate for the small spin-orbit interaction for \(Λ\) observed in hypernuclei recently. Strong spin-isospin dependence of the \(Σ−N\) interaction is yet to be confirmed.

3. The QCM predicts a bound state of \(ΛΛ\), or \(H\) dibaryon, which was not observed so far. We found that the instanton induced interaction gives a strong three-quark repulsion to the \(H\) state, resulting that the bound state shifts to a resonance above the \(ΛΛ\) threshold. Significant enhancement seen in \(ΛΛ\) final states may be a signal for such a resonance state.

§3. Charge Symmetry Breaking (CSB)

The charge symmetry is a symmetry of QCD provided that the \(u\) and \(d\) quarks have the same mass. The symmetry is fairly well satisfied in the hadron spectrum and its interactions, although the \(u−d\) quark mass (QM) difference as well as the electromagnetic (EM) interactions break the symmetry by the order of 1%. For instance, the mass difference of proton and neutron,

\[
M_p - M_n \equiv -\Delta M \simeq -1.3\text{MeV}
\]

comes from the EM contribution, \(\simeq 0.5\) MeV and the QM contribution, \(\simeq -1.8\) MeV. Similar mass differences are observed in the \(Σ\) and \(Ξ\) baryons.

For the two-baryon systems, the charge symmetry predicts the degeneracy of the \(pp\) and \(nn\) systems. After correcting the Coulomb interactions, the scattering lengths of \(pp\) and \(nn\) elastic scatterings show a small difference,

\[
\Delta a \equiv a_{pp} - a_{nn} \simeq 1.5\text{fm}
\]

which is attributed to the charge symmetry breaking. Another interesting observable is the difference of the analyzing power in the \(p−n\) scattering, \(\Delta A \equiv A_p - A_n\).

For nuclear systems, the charge symmetry relates mirror nuclei, a pair of the \((Z, N)\) and \((N, Z)\) nuclei, which have similar level structures, while the charge
symmetry breaking can be observed in the difference in the binding energies, called the Nolen-Schiffer anomaly.

Various origins of the CSB in nuclear force are discussed in the literatures. In the meson exchange picture of the nuclear force, the symmetry is broken by the mixing of $\eta$ meson into the pion, or the mixing of $\omega$ in $\rho$. These effects have been studied but their effects does not give satisfactory explanation of $\Delta a$ and $\Delta A$. This leads us to consider the CSB in the short-range nuclear force.

Thus, it is interesting to study how the quark exchange interaction contributes to the charge symmetry breaking, which is induced by the $u$-$d$ quark mass difference, $\Delta m \equiv m_d - m_u$. A pioneering work by Chemtob and Yang showed that the mass dependence of the color magnetic gluon exchange gives considerable CSB on the $^1S_0$ $NN$ scattering lengths. In an extensive analysis of the nuclear binding energies, Nakamura et al. pointed out the necessity of the short-range CSB, and showed that the quark cluster model gives significant contribution which is consistent with experimental data. However, calculation of $\Delta A$ by Bräuer et al. concluded that the quark exchange contribution is too small for $\Delta A$.

Here I report recent study in collaboration with Nasu and Takeuchi, in which our aim is to describe $\Delta M$, $\Delta a$ and $\Delta A$ simultaneously in the quark model picture of the nucleon. We here assume that the $\Delta m$ for the constituent quarks is of the same order as that of the current quark masses, about 3-5 MeV. We consider the potential quark model hamiltonian

$$H = K + V_{\text{conf}} + (1 - P_{III})V_{\text{OgE}} + P_{III}V_{III} + V_{\text{EM}}$$

(3.1)

Here $V_{\text{conf}}$ is the confinement potential, which does not distinguish $u$ and $d$ quarks, and therefore charge symmetric, and $V_{\text{OgE}}$ is the one-gluon exchange (OgE) potential, whose spin-spin term breaks charge symmetry, i.e.,

$$-(\lambda_i \cdot \lambda_j) \frac{\alpha_s}{4} \left[ \frac{\pi}{m_i m_j} \left( 1 + \frac{2}{3} (\sigma_i \cdot \sigma_j) \right) \delta(r_{ij}) \right]$$

(3.2)

$V_{III}$ is the instanton induced interaction, which is effective only for the $I = 0$ $ud$ quark pair and therefore does not break charge symmetry nor charge independence. It is, however, important to consider $V_{III}$ explicitly because it plays a role to reduce the effect of OgE. $V_{\text{EM}}$ is the Coulomb interaction. The kinetic energy term of quarks depends on the quark masses and therefore contains CSB.

Our aim is to confirm that the quark mass difference in the constituent quark picture gives consistent magnitudes of all three experimental data, $\Delta M$, $\Delta a$ and $\Delta A$. To keep the consistency, we keep our evaluation of the CSB effect up to the lowest order in the perturbation theory throughout our work. In the scattering processes, we evaluate the distorted-wave Born term only and the difference of the $T$-matrix is used to evaluate $\Delta a$ and $\Delta A$.

I cannot go into the detail in this short report, but the summary of our results is given here. Please refer to for details.

1. The mass difference of proton and neutron requires the introduction of $III$, which gives hyperfine splitting of the baryon spectrum but does not induce CSB.
The reason for the importance of $III$ is that the color magnetic interaction of the gluon exchange gives too strong CSB in the wrong direction so that the quark mass difference is essentially cancelled. After introducing $III$, which shares more than 40% of the hyperfine splitting by one gluon exchange interaction, we can explain $\Delta M$. We have determined $\Delta m$ and $P_{III}$ so that the neutron-proton mass difference is reproduced (Table 1).

2. The $^1S_0$ scattering length has been evaluated in the quark cluster model and the results are summarized in Table 1. We find that a large contribution comes from the kinematical effect that is induced by the mass difference of the proton and neutron. Note that the scattering length is inversely proportional to the derivative of the T matrix in terms of the wave number $k$, the baryon mass difference, which changes the dispersion relation should contribute. The results show that the reduced OgE can also explain $\Delta a$.

3. The analyzing powers are calculated by summing the $L = 0, 1, 2$ waves. The antisymmetric $LS$ force is the source of CSB,

$$V_{\text{effCSB}} \propto (\sigma_A - \sigma_B) \cdot L_{AB} \times (\tau_3^A - \tau_3^B)$$

This interaction induces couplings of $^3P_1$ and $^1P_1$, and $^3D_2$ and $^1D_2$, or in general $^3L_L$ and $^1L_L$. In the case of $NN$ scattering these mixings break isospin invariance and charge symmetry. Thus the differences of the analyzing power of the proton and that of the neutron in the $pn$ scattering are direct CSB contribution. Fig. 1 shows the prediction of $\Delta A$ in our QCM calculation, compared with the data from Indiana. The results seem consistent with the data.

| $P_{III}$ | $\Delta m$ [MeV] | $\bar{a}$ [fm] | $\bar{r}$ [fm] | $\Delta a$ [fm] | $\Delta r$ [fm] |
|-----------|-----------------|----------------|----------------|----------------|----------------|
| A         | 0.4             | 7.625          | -17.9          | 2.43           | 1.4            | -1.0          |
| B         | 0.5             | 5.375          | -17.9          | 2.46           | 1.1            | -0.8          |
| Observed  | $-18.1\pm0.4$   | $2.80\pm0.11$  | $1.5\pm0.5$    | $0.1\pm0.12$   |

It should be noted that all the quark model parameters including the CSB interactions are determined in the baryon spectrum in our study and no CSB is induced from the other elements. This is in a sense an extreme because the meson exchange interaction also causes certain amount of the CSB. It is, however, confirmed that the quark mass difference the quark cluster model approach gives significant and consistent amount of the CSB.

§4. Conclusion

The quark cluster model is classic but it still has practical power in describing baryon-baryon interaction. The success of QCM largely owes to the special role of the strangeness. Recent development in hypernuclear physics, in which interactions of strange baryons are studied extensively, provided us with qualitatively new information on the baryon-baryon interactions. Further development is expected to
make the mechanism of the baryon-baryon interactions much clearer than our present knowledge.

In this talk, I have discussed the charge symmetry breaking in the $NN$ interaction from the QCM viewpoint and have shown that a consistent picture can be drawn by assuming the CSB comes from the short range part of the interactions. It is yet to be concluded how the long-range and short-range parts share the roles in CSB in nuclear force, but it is significant that the contribution of the short-range part is important.

The main part of this work has been done in collaboration with Takashi Nasu and Sachiko Takeuchi.

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