Contributions from Goldstone-boson-exchange to baryon spectra in the MIT Bag Model

Da-Heng He$^1$, Yi-Bing Ding$^2$, Xue-Qian Li$^1$ and Peng-Nian Shen$^3$

1. Department of Physics, Nankai University, Tianjin, 300071, China.
2. Institute of Physics, Graduate School of Chinese Academy of Sciences, Beijing, 100049, China.
3. Institute of High Energy Physics, P.O.Box 918-4, Beijing, 100049, China.

Abstract:
We discuss contributions of chiral bosons to baryon spectra in the MIT bag model. It is believed that within hadrons, chiral bosons are degrees of freedom which are independent of gluons to provide strong interactions between quarks. In the original MIT bag model, only interaction mediated by gluon exchanges was considered, by contrast, in this work we take into account the interaction mediated by the exchanges of chiral bosons $\sigma$ and $\pi^{(\pm,0)}$. Then following the standard approach, we minimize the effective hamiltonian which includes both the contributions from gluon and chiral-boson exchanges with respect to the bag radius to obtain the effective radius. By re-fitting the spectra of baryons, we find that the contributions from the boson-exchange may be 40% of that from gluon-exchanges and meanwhile the bag constant $B$, the zero-point energy $z_0$ almost do not change. It indicates that in the original version of the MIT bag model, the intermediate-distance interaction due to the chiral-boson exchanges is attributed into the effective coupling $\alpha_c$ which stood for the short-distance interaction caused by the gluon exchanges and the long-distance effects reflected by $B$ and $z_0$ are not influenced.

I. Introduction

It is generally believed that QCD is the successful theory for strong interaction and nowadays, nobody ever doubts its validity. Due to the asymptotic freedom, at higher energy processes, all the physical quantities, such as cross sections, can be calculated perturbatively and the results are very accurate. However, when we deal with the hadron physics, the typical energy scale is $\Lambda_{QCD} \sim 200$ MeV, at this region, the non-perturbative QCD effects dominate and
any perturbative QCD calculations become questionable. So far, there are no reliable ways to properly handle the non-perturbative QCD based on any underlying principles.

To evaluate the hadron spectra and their hyperfine structure etc., one needs to invoke some concrete models which may implement the non-perturbative behaviors of QCD into the models and concerned parameters. The traditional methods include the potential model, MIT bag model and many others. In all the models, the short-distance interaction between quarks is induced by exchanging hard gluons and the leading order is the one-gluon exchange. But the ways to describe the long-distance effects of QCD are different for different models. For example, in the potential model, a confinement term is phenomenologically introduced and the concerned parameters must be obtained by fitting data. There are several commonly adopted forms for the confinement term, and the most common one is the linear potential which seems to be consistent with the lattice results.

For the MIT bag model, a rigid bag-boundary which prevents outward flux of quarks, replaces the linear potential to provide the confinement. Inside the bag, quarks, at the zeroth order approximation, are free of interactions, and obey the Dirac equation for free fermion with a non-trivial boundary condition, i.e. the outward flux is zero at the bag boundary. Then at the next-to-leading order, one needs to take interactions among quarks into account. As DeGrand et al.[1] suggested, to this approximation, the one-gluon exchange is responsible for the interaction which can be expressed as couplings of the magnetic dipole moments of quarks, obviously, it is equivalent to the description where the interaction energy is achieved in terms of the one-gluon-exchange mechanism according to the quantum field theory. We have applied the method to evaluate the spectra of baryons which contain two heavy quarks (b and/or c)[2].

When evaluate the energy caused by the effective interaction between quarks, one needs to sandwich hamiltonian induced by the one-gluon-exchange between the zeroth order wavefunctions of quarks and calculate the expectation values. The expectation values are the interaction energy between quarks. So far, the whole procedure is perturbative, but later on, one needs to obtain a new bag radius by minimizing the total energy which includes both the zeroth order and newly derived next-to-leading order contributions, with respect to the bag radius. Therefore
the bag model treatment is not totally perturbative.

Moreover, many research works indicate that in hadrons, not only gluons and quarks, but also the chiral bosons, such as $\sigma$, $\pi$ and even kaons, can be independent degrees of freedom [3, 4, 5, 6]. Namely, exchange of chiral bosons is not included in exchange of hard multi-gluons. The gluons are the QCD gauge bosons and possess color charges, so that they interact among themselves. At lower energies, they cannot propagate far, therefore can only be responsible for short-distance interaction. If one demands that the one-gluon exchange determines only the short-distance interaction, a long-distance interaction which cannot be derived in the framework of perturbation, is responsible for the confinement. Is the picture too simplified? In other words, it should be asked if the intermediate-distance interaction needs to be independently evaluated, i.e. separated from both short- and long-distance interactions as a distinct one.

Some authors suggest that in hadrons the asymptotic freedom[7] completely applies and the exchange of hard gluons does not contribute to the spectra at all. Instead, only the intermediate-distance and long-distance interactions contribute. For example in the QMC Model[8, 9, 10, 11], only chiral bosons ($\sigma, \pi, K$) and light vector bosons ($\rho, \omega, \phi$) are considered. It is interesting to notice that the propagator of a chiral boson $e^{-mr}$ seems to be more suppressed at larger distance than the propagator of gluon $\frac{1}{r}$. But it is in the perturbative sense. As a gauge boson of Yang-Mills gauge field[12], gluons interact among themselves and cannot propagate far, by contrary, the chiral boson is color-singlet, so that does not suffer from this constraint. The interaction induced by exchange of chiral bosons can be considered as the intermediate-distance interaction.

It is natural to ask if one can omit any of the three kinds of interactions which come from different aspects of QCD. Phenomenologically, the question is if we can attribute any of the interactions into the others by adjusting the concerned parameters. By the literature, it is definitely plausible for estimation of hadron spectra, but then the physics picture is not complete and maybe, some hyperfine properties of hadrons would be smeared away. Thus, we may wish to re-study the physics picture by including all the three interactions and see if a complete physics picture can be built up. Based on the commonly accepted principles, we study the contributions
from the short-distance effects which are induced by the hard-gluon exchanges, intermediate-distance contributions which are caused by the exchanges of chiral bosons and the long-distance effects in a unique framework. Namely, we investigate their respective contributions in the MIT bag model where the long-distance effects are provided by the bag-boundary and perhaps, also the zero-point energy.

Our strategy in this work is that the effective hamiltonian which accounts for contributions from both the hard-gluon exchange and chiral-boson-exchange, is sandwiched between the zeroth order wavefunctions of quarks to obtain a total energy, while the long-distance effects are reflected in the bag-boundary condition of the Dirac equation. The effective vertices between quark and chiral bosons are described by the linear $\sigma$ model where the $\sigma$ boson remains as an independent particle. After obtaining the total energy, we minimize it with respect to the bag radius, and the minimum is supposed to correspond to the hadron spectra. Indeed, there is a zero-point energy which should be included and determined by fitting data. It is natural to suppose that it is a universal for all the baryons and can be fixed by experimental data. The same problem exists in the potential model in fact.

More concretely, based on the principles and rules of quantum field theory, we formulate the effective hamiltonian and evaluate the contribution from the intermediate-distance interaction to the total energy, which is caused by exchanging chiral bosons.

We also briefly discuss possible contributions of three-body interactions. Namely it seems that the three constituent quarks may interact via a three-gluon vertex, but a symmetry analysis [13] indicates that the net contribution is null due to the color-singlet requirement for hadrons. Then we consider the three-body intermediate-distance interaction via a $\sigma - \pi - \pi$ coupling, since the corresponding structure is very complicated, it is difficult to reach a complete solution. Instead, we are going to estimate the order of magnitude of such contribution. Only considering a simplified breathing mode which is believed to be the leading mode, we qualitatively and half-quantitatively evaluate its contribution and find that it is much smaller than the two-body interaction and can be negligible for practical computations.
This work is organized as follows. After this long introduction we present the formulation for the interaction between quarks which are caused by exchange of chiral mesons based on the principles and Feynman rules of quantum field theory. In Sec.III, we present the numerical results where the concerned parameters and inputs are listed out explicitly. Then in Sec.IV, we discuss the three-body interactions, derive the formulation of the effective hamiltonian for the breathing mode which is a simple and rough approximation, we give our numerical estimates. The last section is devoted to our conclusion and discussions.

II. Formulation

The short-distance interactions caused by gluon exchanges have already been well formulated in the original works about the MIT model[1]. The color magnetic interaction energy is written as

\[ \Delta E_m = 8\alpha_c \lambda \sum_{i>j} \frac{\mu(m_i,R)\mu(m_j,R)}{R^3} I(m_iR,m_jR)(\vec{\sigma}_i \cdot \vec{\sigma}_j), \]

and the expressions of \( \mu(m,R) \) and \( I(m_iR,m_jR) \) are given in [1]. As DeGrand et al. proved, the color-electric interaction energy is quite small and we can simply ignore it.

The one-gluon-exchange results in a short-distance interaction and \( \Delta E_m \) is included in the total energy. As argued in [3, 4, 5, 6], the chiral boson exchange could be independent of the one-gluon-exchange and corresponds to the intermediate-distance interaction. Now let us turn to the interacting energy which is caused by chiral boson-exchange.

The formulation to be used is directly derived from the principle of quantum field theory[2, 14]:

\[ E_{int} = \int \bar{\psi}_1 \Gamma_1 \psi_1 D_{prop} \bar{\psi}_2 \Gamma_2 \psi_2 d^3x d^3y, \]

where \( \psi_1, \psi_2 \) are the zeroth order bag wave functions of two interacting quarks, \( D_{prop} \) is the gauge boson propagator in coordinate space and \( \Gamma \) is the coupling vertex.

First of all, for quark-meson coupling, the chiral lagrangian in SU(2) is[15]:

\[ \mathcal{L}_{NP} = i\bar{\psi}(\gamma^\mu \partial_\mu - m)\psi + g\bar{\psi} \Sigma \psi, \]
where
\[ \Sigma = \sigma + i \gamma_5 \tau \cdot \pi, \]  
and \( g \) is the effective coupling constant between scalar or pseudoscalar meson and quarks in linear \( \sigma \) model. To achieve this effective coupling constant \( g \), one may use the data of \( p - p \) scattering and the quark-hadron relation. However, in our case, this method seems not work. Because for evaluating the spectra, the quarks are confined and the effective coupling should be close to the the value employed in the potential model which is gained by fitting the baryon spectra. In fact, here we just keep \( g \) as a free parameter and determine it by fitting data and then compare its value with that in the potential model and see if it makes sense.

This SU(2) linear \( \sigma \) model can be extended into SU(3) space and applied to the calculations in the MIT bag model.

In SU(3) space, \( \Sigma \) is generalized as [16, 17]:
\[ \Sigma = \sigma + i \gamma_5 T^a \phi^a_p, \]  
and
\[ T^a \phi^a_p = \sqrt{2} \begin{pmatrix} \pi^0 + \eta & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \frac{K^0}{\sqrt{2}} & -\sqrt{\frac{2}{3}} \eta \end{pmatrix}. \]  
The propagator of chiral boson in the instantaneous approximation i.e \( q_0 = 0 \) is:
\[ D_{\text{prop}}(q) = \frac{1}{q^2 + m^2}. \]  
By a Fourier-transformation, we can write it in the coordinate space as:
\[ D_{\text{prop}}(r) = \int e^{i \mathbf{q} \cdot \mathbf{r}} \frac{1}{q^2 + m^2} \frac{d^3 \mathbf{q}}{(2\pi)^3} = e^{-m |\mathbf{r}|}. \]  
where \( r \) is the relative distance between two interacting quarks. With these theoretical preparations, we will derive the formulation of the interacting energy due to one-meson-exchange:
\[ E_{\text{qqq}} = \int q_1(x_1)gq_1(x_1)e^{-M_\sigma r} q_2(x_2)gq_2(x_2)d^3x_1d^3x_2 \]
\[ = g^2 \frac{N^2}{4\pi} \int \left[ j_0^2 \left( \frac{\chi x_1}{R} \right) - J_1^2 \left( \frac{\chi x_1}{R} \right) \right] e^{-M_\sigma r} \frac{r}{R} \left[ j_0^2 \left( \frac{\chi x_2}{R} \right) - J_1^2 \left( \frac{\chi x_2}{R} \right) \right] d^3x_1d^3x_2, \]
\[ E_{q\sigma q} = \sum_p \int \overline{q}(x_1) i g \gamma^5 q_1(x_1) \frac{e^{-M_{\sigma} r}}{4\pi r} \overline{q}(x_2) i g \gamma^5 q_2(x_2) d^3x_1 d^3x_2 \]

\[ = \sum_p \frac{g^2}{4\pi} 4N^2 \int j_0(\frac{\chi_{x_1}}{R}) j_1(\frac{\chi_{x_1}}{R}) (\sigma_1 \cdot x_1) e^{-M_{\sigma} r} \]

\[ \times j_0(\frac{\chi_{x_2}}{R}) j_1(\frac{\chi_{x_2}}{R}) (\sigma_2 \cdot x_2) d^3x_1 d^3x_2 \]  \hspace{1cm} (10)

where \( E_{q\sigma q} \) is the interacting energy due to \( \sigma \) meson exchange and \( E_{qpq} \) is a sum of the contributions of various pseudoscalar mesons. \( q_1(x_1) \) and \( q_2(x_2) \) are wave functions of quarks; \( N \) is the normalization constant; \( M_{\sigma}, M_p \) are the masses of the corresponding scalar and pseudoscalar mesons.

In the calculation, one finds that the integration (13) (14) would turn infinite when

\[ r = |x_1 - x_2| \rightarrow 0. \]  \hspace{1cm} (11)

No doubt, such infinity is only formal, if one can deal with a whole computation properly, this divergency should disappear. To avoid this problem, we introduce a new coordinate system:

\[ x_1 = X, \]

\[ x_1 - x_2 = Y. \]  \hspace{1cm} (12)

Replacing coordinate \( x_1, x_2 \) by \( X, Y \), we have

\[ E_{q\sigma q} = g^2 \frac{N^2}{4\pi} \int [j_0^2(\frac{\chi_{X}}{R}) - j_1^2(\frac{\chi_{X}}{R})] d^3X \times \]

\[ \int e^{-M_{\sigma}|x_1 - x_2|} [j_0^2(\frac{\chi_{x_2}}{R}) - j_1^2(\frac{\chi_{x_2}}{R})] d^3x_2 \]

\[ = g^2 \frac{N^2}{4\pi} \int [j_0^2(\frac{\chi_{X}}{R}) - j_1^2(\frac{\chi_{X}}{R})] d^3X \times \]

\[ \int [j_0^2(\frac{\chi{|X-Y|}}{R}) - j_1^2(\frac{\chi{|X-Y|}}{R})] e^{-M_{\sigma}Y} Y D^3Y, \]  \hspace{1cm} (13)

and

\[ E_{qpq} = g^2 \frac{N^2}{4\pi} \int j_0(\frac{\chi_{x_1}}{R}) j_1(\frac{\chi_{x_1}}{R}) (\sigma_1 \cdot x_1) d^3x_1 \times \]

\[ \int e^{-M_p|x_1 - x_2|} \frac{j_0(\frac{\chi_{x_2}}{R}) j_1(\frac{\chi_{x_2}}{R}) (\sigma_2 \cdot x_2) d^3x_2}{|x_1 - x_2|} \]
\[ E_{\sigma q} = \frac{g^2}{4\pi} N_1^2 N_2^2 (\sigma_1 \cdot \sigma_2) \int_0^R \frac{j_0(\frac{X}{R}) j_1(\frac{X}{R})}{X^2} dX \times \int_0^\pi \sin \theta d\theta \int_0^{f(\theta)} \frac{j_0^2(\frac{X}{R})}{X^2} - j_1^2(\frac{X}{R}) \right] e^{-M_\sigma Y} Y dY, \] (16)

and

\[ E_{\sigma q} = \frac{g^2}{4\pi} N_1^2 N_2^2 \left( \frac{\sigma_1 \cdot \sigma_2}{X} \right) \int_0^R \frac{j_0(\frac{X}{R}) j_1(\frac{X}{R})}{X^2} dX \times \int_0^\pi \sin \theta d\theta \int_0^{f(\theta)} j_0(\frac{X}{R}) j_1(\frac{X}{R}) \frac{X}{|X - Y|} e^{-M_\sigma Y} Y dY. \] (17)

Below, we will turn into numerical computations.

III. Numerical Results

As discussed above, we hope to take both short-distance and intermediate-distance interaction into account to get a more complete physics picture of strong interaction among quarks in hadrons. Namely, quark-gluon coupling and quark-meson coupling are considered simultaneously. In this work, we still follow the general strategy given by the MIT bag model, namely, summing over the contributions of the short-distance and intermediate-distance interactions which are discussed in last subsection, as well as the bag vacuum energy \( \frac{4}{3} \pi R^3 B \) and zero point energy \( \frac{Z}{R} \) to constitute the total energy and then differentiate it with respect to the bag radius.
to obtain an effective bag radius. Substituting the radius into the expression of the energy, we obtain the formulation of the baryon mass spectra. Then we need to fix the concerned parameters by fitting data. In this new version, there are four parameters to be fixed, $\alpha_c$, $\alpha_M$, $B$ and $Z_0$.

In the original paper on the bag model, the authors gave two sets of $B$ and $Z_0$, here we only choose one set. We tried to vary the values of $B$ and $Z_0$ near the original ones and to see if we can fit the spectra. We find that it is hard to get satisfactory results no matter how we change these two parameters.

The new parameter $\alpha_M$ which did not exist in the original version of the MIT bag model, is to be fixed by fitting the rich spectra of baryon octet and decuplet. In the potential model, Glozman et.al. obtained a value for the quark-meson coupling constant [18]. Since the short-distance and intermediate-distance interactions have different algebraic structures, the corresponding effective couplings are irrelevant, so that in principle there may be several possible choices. But we find that only certain combinations can best fit the data. It is hinted that the value of $\alpha_M$ achieved by Glozman et.al [18] in the potential model may be appropriate for the spectra evaluation, we would choose the value of $\alpha_M$ close to that of [18]. By varying their values, we obtain the best fit to the spectra. Then we can compare our result with theirs. We finally find that a combination of parameters: $B^{1/4} = 0.145$, $Z_0 = 1.84$, $\alpha_c = 0.398$, $\alpha_M = 0.545$ can well accommodate the experimental spectra of baryons.

We find our result about $\alpha_M$ which is a phenomenological coupling constant between quark and chiral bosons is consistent with that obtained by Glozman et al. in the potential model. With the parameters, the fitted results are shown in the following label:
Table 1. The concerned results, as a comparison we list the results given in the earlier work for the MIT bag model.

### IV. Qualitative and semi-quantitative study on three-body interactions

Besides the one-gluon and one-meson exchange between two quarks, there also could be interactions among all three quarks in nucleon via a triple gluon vertex or $\sigma\pi\pi$ coupling vertex. Such coupling processes are three-body interactions. For triple gluon coupling case, as argued in [13], the interacting energy is proportional to:

$$f^{abc}\epsilon_{ijk}\epsilon_{i'j'k'}\lambda^a_{ii'}\lambda^b_{jj'}\lambda^c_{kk'},$$

(18)

analysis indicates that due to the requirement of color singlet for hadrons, this contribution of such an interaction is null.

Then we turn to the $\sigma\pi\pi$ case.

Following the procedure before, there is a product of three propagators:

$$\frac{1}{p^2 + m_\sigma^2} \times \frac{1}{q^2 + m_\pi^2} \times \frac{1}{p^2 + m_\pi^2},$$

(19)

where $l, \mathbf{q}, \mathbf{p}$ are the 3-momentum of $\sigma, \pi, \pi$ respectively. By the momentum conservation, it is:

$$\frac{1}{(p + q)^2 + m_\sigma^2} \times \frac{1}{q^2 + m_\pi^2} \times \frac{1}{p^2 + m_\pi^2}.$$

(20)

To get the final form in the coordinate space, we make a Fourier-transformation first on $\mathbf{q}$:

$$\int A e^{i\mathbf{q} \cdot \mathbf{r'}} \frac{d^3q}{(2\pi)^3} = \frac{1}{4\pi^2} \frac{e^{-m_\sigma r'}}{(p - i(m_\sigma - m_\pi))(p + i(m_\sigma + m_\pi))}$$

$$+ \frac{(-p + im_\sigma)e^{-ipr'}}{im_\sigma(p - i(m_\sigma - m_\pi))(p - i(m_\sigma + m_\pi))}.$$  

(21)
where

\[ A = \frac{1}{(p + q)^2 + m_\sigma^2} \times \frac{1}{q^2 + m_\pi^2} \]  

(22)

Then on \( p \):

\[
V_{\text{prop}} = \int \frac{B}{p^2 + m_\pi^2} e^{i p \cdot r} \frac{d^3p}{(2\pi)^3} - \frac{1}{4\pi r} \left( \frac{e^{-m_\sigma(r+r')}}{(m_\sigma + 2m_\pi)(m_\sigma - 2m_\pi)} - \frac{(m_\sigma - m_\pi) e^{-(m_\sigma)(r'-r)}}{(m_\sigma - 2m_\pi)m_\sigma^2} + \frac{(m_\sigma + m_\pi) e^{m_\sigma(r'-r)}}{(m_\sigma + 2m_\pi)m_\sigma^2} \right),
\]

(23)

where

\[
B = \left[ \frac{e^{-m_\sigma r'}}{(p - i(m_\sigma - m_\pi))(p + i(m_\sigma + m_\pi))} \right. \\
+ \left. \frac{(-p + im_\sigma)e^{-ipr'-m_\sigma r'}}{im_\sigma(p - i(m_\sigma - m_\pi))(p - i(m_\sigma + m_\pi))} \right].
\]

(24)

Eq.(26) provides us the "formal" propagator in \( \sigma \pi \pi \) coupling process. Then the interacting energy caused by the three-meson coupling is written as:

\[
E_{\sigma \pi \pi} = -g_{\sigma \pi \pi} \int \bar{\psi}_1 \gamma_1 \psi_1 V_{\text{prop}} \bar{\psi}_2 \gamma_5 \psi_2 \bar{\psi}_3 \gamma_5 \psi_3 d^3xd^3yd^3z
\]

(25)

where \( g_{\sigma \pi \pi} \) is the coupling vertex calculated in [19, 20]:

\[
g_{\sigma \pi \pi} \sim 2\text{GeV}
\]

(26)

The complete calculation is very difficult, so we would estimate its order of magnitude in a simplified scenario where only the "breathing mode" is considered. It means that although the three quarks can reach any point in the bag, the relative angles among them remains at 120°, and the relative spacial distances among them are the same all the time. Then we can calculate the three-body interacting energy with the simplified scenario. Numerical integration on computer indicates that the upper limit of \( E_{\sigma \pi \pi} \sim 0.005\text{GeV} \), which is much smaller than that by the one-gluon and one-meson exchanges. Therefore with the present experimental accuracy, we need not take this contribution into account at all. Although this picture is rough, one can
expect that it can at least give the right order of magnitude of such interaction.

V. Conclusion and Discussions

Quarks and gluons are confined inside hadrons by strong interaction which is described by QCD. Due to the asymptotic freedom, the quarks which are close to each other are approximately free of interaction and it is the basic point of the MIT bag model, in which the quarks obey the Dirac equation for free fermions with a bag boundary condition. Indeed it is the non-perturbative QCD effects which correspond to the long-distance interaction and bind quarks into a hadron. Even though the potential model looks quite different from the MIT bag model, basically, they are somehow equivalent and just the linear or some other confinement potentials replace the bag boundary in the MIT bag model. Since so far, there lacks a reliable way to approach the non-perturbative QCD and a unique picture from quark-gluon degrees of freedom to the hadron phase cannot be derived from any underlying theory.

It is generally believed that the one-gluon exchange which obviously represents the leading order in QCD, corresponds to the short-distance interaction between quarks. In the MIT bag model, it is accounted as a correction to the total energy and its contribution is evaluated in perturbation method. On other side, the chiral boson-exchanges are also supposed to contribute an intermediate-distance interaction which also plays a role to bind quarks in hadrons. It is argued [3, 4, 5, 6] that the chiral bosons are also interaction agents between quarks and correspond to degrees of freedom which are independent of gluons at the energy region of \( \Lambda_{QCD} \). Moreover, some authors[8, 9, 10, 11] claim that the gluon-exchange can be dropped out due to the asymptotic freedom and only the chiral-boson-exchanges apply or at least dominate. It seems to contradict to the approach of the MIT bag model and this problem concerns the fundamental physics picture, so is worth careful investigation, i.e. if the two pictures are consistent. In this work, we just include the contribution from both gluon-exchange and chiral-boson-exchange to the total energy and see if the results make sense. The purpose of this work is not to gain any better phenomenological predictions which can be experimentally tested, but tries to clarify the physics picture and see if one can accommodate the short-, intermediate- and long-distance
interactions in a unique framework. Definitely, the MIT bag model among various models for hadron spectra provides an ideal place to study this subject.

In this work, we only consider the exchanges of $\sigma$ and $\pi(\pm, 0)$ and ignore the contributions from exchanges of vector mesons because they are much heavier than the scalar and pseudoscalar mesons. Since we obtain the corresponding parameters by fitting data, there exist certain errors coming from experimental measurement, especially for the heavier members of the baryon octet and decuplet. Moreover, we need a set of parameters and the spectra of well measured baryons can determine all of them. In particular, we determine the effective quark-meson coupling and compare the value with that obtained in potential model. We find that our result is consistent with the given by Glozman et al [18]. For being more confident with the results, we also roughly estimate the three-body interactions among the three valence quarks. The Lie algebra indicates that the interaction via the three-gluon vertex is null due to the color singlet requirement for baryons, whereas the interaction via $\sigma\pi\pi$ vertices can result in non-zero contributions. Since a complete calculation is extremely difficult, we only use a simplified picture, namely only the breathing mode is considered, to estimate the order of magnitude of such three-body interaction. We find that this contribution is much smaller than the two-body interactions and generally can be safely ignored from practical calculations. We admit that because this treatment is very simplified, the result may deviate from the real value, however, we believe that the order of magnitude must be correct and the qualitative conclusion about the size of the three-body interaction is close to reality.

By our numerical results, we can conclude our findings as following.

Letting the differentiation of the total energy which is a function of the bag radius $R$ with respect to $R$ be zero, we obtain the radius $R$, and the total energy with this $R$—value is a minimum and supposed to be the real mass of the baryon. The expression of the total energy includes contributions from the energy-eigenvalues of free quarks which corresponds to the zeroth order of strong Hamiltonian, single-gluon-exchange, chiral-meson-exchange, the vacuum pressure term $\frac{4}{3}\pi R^3 B$ and the zero-point energy $\frac{Z_0}{R}$. By re-fitting the well-measured baryon spectra, we have obtained the concerned parameters which are listed in last section. Comparing with
the parameter values obtained in the early works about the MIT bag model where only one-gluon-exchange was considered, the best fit to the data shows that the contribution from the intermediate-distance effect induced by chiral-meson-exchanges can be as large as 40% of that from short-distance effect induced by gluon-exchange, while the $B^-$ and $Z_0^-$ values remain unchanged. This fact indicates that inclusion of the chiral-boson exchanges which induce the intermediate-distance interaction, changes the effective coupling $\alpha_c$ of the previous work where only short-distance interaction was considered, but does not affect the long-distance interaction which is manifested by $B$ and $Z_0$. As a conclusion, in a complete picture, both short-distance and intermediate-distance interactions should be involved, however, if one uses an effective coupling for either short-distance (gluon-exchange) or intermediate-distance (chiral-boson-exchange), the phenomenology is the same, but the effective coupling would have different values.

Indeed, in this work, we ignore contributions from vector mesons because of their heavier masses and couplings and also omit the three-body interaction because of its smallness in comparison with the two-body interactions. This treatment may bring up certain errors definitely, but should not influence our qualitative conclusion.

Even though there is no any difference for evaluating spectra of baryons as long as one uses right effective coupling in either of the two scenarios, namely only considers one type of exchanges, gluon or chiral bosons, the difference may manifest itself when evaluating some dynamical processes, such as decays. We will further investigate these processes in our later works.

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