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The Effective Two-Meson-Exchange Potential Derived From the Quark-Antiquark Pair Creation Model

Yu Youwen and Shen Pengnian

(Institute of High Energy Physics, Chinese Academy of Sciences, Beijing and Center of Theoretical Physics, CCAST (World Laboratory))

The effective two-meson-exchange potential with regard to the box diagram in the N-N interaction has been derived by virtue of the one-gluon-exchange quark-antiquark pair creation model. The result shows that the general feature of this effective potential agrees with that of the phenomenological σ-meson exchange potential in the coordinate space.

1. INTRODUCTION

It is well known that in the meson-exchange theory of the nuclear force, the long-range part of the nuclear force is normally interpreted as the one-pion exchange potential, the medium-range part of the nuclear force is mainly attributed to the two-pion exchange and the short-range part of the

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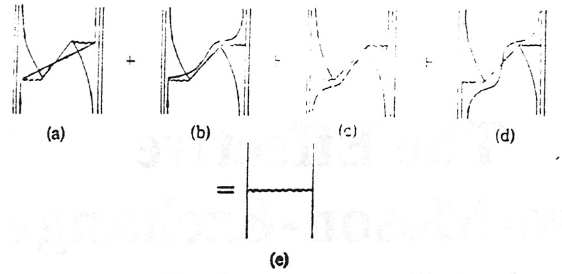

FIG.1 Effective one-meson exchange potential.

nuclear force has to be offered phenomenologically [1]. In our previous investigations, we have proposed a model in which quark-antiquark pair (q-$\bar{q}$) is created via the one-gluon exchange [2] and calculated the effective one-meson exchange potential intervening between two nucleons. The result shows that the medium- and long-range parts of this effective potential are very similar to the corresponding parts of the nuclear force in the meson-exchange theory [3]. In the present work, our purpose is to investigate whether the medium-range attraction could be given or partly given by considering the effective two-meson exchange potential in the quark-antiquark pair creation model. This is a very difficult but meaningful problem. Therefore, under some approximation, we have calculated the contributions of the box diagrams, in which the intermediate states are two particle states, to the nucleon-nucleon interaction and compared this result with that of the σ-meson exchange potential. The result shows that general features in both cases are the same.

In the following section, the effective two-meson exchange potential is derived. Finally in section 3, results and discussions are given.

2. EFFECTIVE TWO-MESON EXCHANGE POTENTIAL

From the viewpoint of the quark-antiquark pair creation via one-gluon exchange, the propagated intermediate quark-antiquark pairs in diagrams (a), (b), (c), and (d) in Fig.1 could be in the color-singlet states and could have quantum numbers of mesons, hence their functions could be considered an effective one-meson exchange potential intervening between two nucleons (see diagram (e) in Fig.1). This effective one-meson exchange potential intervening between two nucleons is presented in diagram (e) in Fig.1, and the exchange meson can be either π, ρ, η, η', ω, or ϕ-meson.

In the previous paper, the matrix element of the hadron-meson vertex for the $B_1 \rightarrow B_2 M$ process in the quark-antiquark pair creation model was written [3,4] as

$$M_{B_1B_2M}(Q) = i\sqrt{4\pi}\,\frac{f_{B_1B_2MI}}{m_M\sqrt{2\omega_M}}\,F_{B_1B_2M}(Q)\,\boldsymbol{\sigma}_{B_2B_1}\cdot\mathbf{Q}\,\boldsymbol{\tau}_{B_2B_1} \tag{1}$$

for the pseudoscalar meson,

$$M_{B_1B_2M}(Q) = i\sqrt{4\pi}\,\frac{f_{B_1B_2M}}{m_M\sqrt{2\omega_M}}\,F_{B_1B_2M}(Q)(\boldsymbol{\sigma}_{B_2B_1}\times \mathbf{Q})\boldsymbol{\tau}_{B_2B_1}. \tag{2}$$

for the pseudovector meson.

By using vertex functions (1) and (2), the general form of the interaction transition potential of the process in which two baryons B_1 and B_2 change into two baryons B_3 and B_4 through the exchange of meson M can be easily obtained. In the momentum space, it can be expressed in the following form:

$$V^M_{B_3B_4,B_1B_2}(Q) = -4\pi\,\frac{f_{B_1B_3M}f_{B_2B_4M}}{m_M^2}\,F_{B_1B_3}(Q)F_{B_2B_4}(Q)$$
$$\times\,(\boldsymbol{\sigma}_{B_3B_1}(1)\cdot\mathbf{Q})(\boldsymbol{\sigma}_{B_4B_2}(2)\cdot\mathbf{Q})\,\frac{1}{2\omega_M}\left[\frac{1}{E_{B_3}+\omega_M-E_{B_1}}+\frac{1}{E_{B_4}+\omega_M-E_{B_2}}\right]$$

for the pseudoscalar meson, (3)

$$V^M_{B_3B_4,B_1B_2}(Q) = -4\pi\,\frac{f_{B_1B_3M}f_{B_2B_4M}}{m_M^2}\,F_{B_1B_3}(Q)F_{B_2B_4}(Q)$$
$$\times\,(\boldsymbol{\sigma}_{B_3B_1}(1)\times\mathbf{Q})\cdot(\boldsymbol{\sigma}_{B_4B_2}(2)\times\mathbf{Q})\,\frac{1}{2\omega_M}\left[\frac{1}{E_{B_3}+\omega_M-E_{B_1}}+\frac{1}{E_{B_4}+\omega_M-E_{B_2}}\right]$$

for the vector meson, (4)

When the exchanged meson M is an isospin-vector meson, an additional factor $\tau_{B_3B_1}(1)\cdot\tau_{B_4B_2}(2)$ should be attached. In Eqs.(3) and (4), m_M and Q are the mass and the momentum of the meson M, respectively, E_B and ω_M are the masses of baryon B and meson M, respectively, $f_{B_1B_3M}$ and $F_{B_1B_3M}(Q)$ are the vertex coupling constant and form factor with $F_{B_1B_3M}(Q=0)=1$, respectively, and $\sigma_{B_3B_1}$ and $\tau_{B_3B_1}$ are transition operators of the spin and isospin from baryon B_1 to baryon B_3, respectively. If B_1 and B_3 are nucleons, $\sigma_{B_3B_1}$ and $\tau_{B_3B_1}$ are normal Pauli spin and isospin operators. By further performing the Fourier transform for $V(Q)$, the effective one-meson exchange potential in the coordinate space can be written as

$$V^M_{B_3B_4,B_1B_2}(r) = \frac{1}{(2\pi)^3}\int V^M_{B_3B_4,B_1B_2}(Q)e^{i\mathbf{Q}\cdot\mathbf{r}}d\mathbf{Q}. \tag{5}$$

Thus, the effective two-meson exchange potential can be constructed by using the effective transition potential in Eq.(5). It has been pointed out that the effect of the isobar Δ-thelowest excited state of the nucleon, must be included in the expression of the interaction in the N-N system. Hence the appearance of NΔand ΔΔexcitations must be considered in the calculation of the N-N interaction, namely, the contributions from intermediate states NΔ and ΔΔ to the N-N interaction should be taken into account in the evaluation of the two-meson exchange potential. By making the adiabatic approximation for intermediate states, the effective two-meson exchange potential via the Δ excitation in the N-N system can be expressed as

$$V^{2M}_{NN,NN}(r) = V^M_{NN,N'\Delta}(r)\,\frac{1}{E_\Delta+E_{N'}-2E_N}\,V^M_{N'\Delta,NN}(r)$$
$$+\,V^M_{NN,\Delta\Delta}(r)\,\frac{1}{E_\Delta+E_\Delta-2E_N}\,V^M_{\Delta\Delta,NN}(r). \tag{6}$$

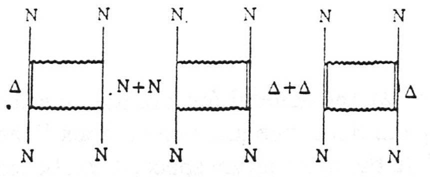

FIG.2 Two-meson exchange processesin the N-N interaction.

The effective two-meson exchange potential described by Eq.(6) is composed of two effective one-meson transition potentials and one intermediate state energy propagator. This means that the contributions from those box diagrams, in which the intermediate state consists of two baryons only, are taken into consideration, if Eq.(6) is used in the two-meson exchange potential calculation (see Fig.2 in Section 3).

3. RESULTS AND DISCUSSION

Since the isospin of the intermediate particle Δis 3/2, among the lower mass mesons only π- and ρ-mesons can participate in this two-meson exchange process. In this investigation, we have evaluated the contributions from those diagrams in Fig.2. According to Eq.(6), one can give the effective two-meson exchange potential by evaluating the one-meson transition potential and the energy propagator. It should be particularly emphasized that in the calculation of the one-meson transition potential, $V_{N\Delta,NN}$ and $V_{\Delta\Delta,NN}$, the transition potentials which produce intermediate states in the two-meson exchange process are different from the one-meson exchange potential in real processes. The momenta of N and Δin the real processes are constants. However, the momenta of both intermediate N and Δand the momentum of the exchanged meson in the two-meson exchange process are variable. The only constraint on these momenta is the momentum conservation relation. Moreover, it is very difficult to calculate the energy propagator rigorously. At this moment, we take $E\Delta - M_N$ = 294 MeV, the static mass difference between Δand N, as the energy denominator. This is a useful way to qualitatively study the property of the effective two-meson exchange potential, although it is a rather rough approximation. In the calculation, we take the same values of the quark-gluon coupling constant α_s and the quark mass m as those used in our previous papers, namely, α_s = 1.39 and m = 300 MeV[2,3]. We also take the value of the size parameter of the nucleon to be 0.5 or 0.6 fm as usual. In order to compare the result with those obtained in other similar investigations, we chose the values of the nucleon and isobar size parameters to be 0.5 fm, meanwhile, the values of the π- and ρ-meson size parameters to be 0.45 fm. It should be pointed out that the calculated result would shift to some extent with changed parameters, but the general feature remains the same.

The comparisons between the effective two-meson exchange potential and the phenomenological σ-meson exchange potential with respect to r in both ST = (0,1) and (1,0) cases are shown in Figs.3a and 3b, respectively. The dashed curves represent the results calculated by using Eq.(6) in this model, while the solid curves represent the phenomenological σ-meson exchange potentials. Since the methods to obtain the phenomenological σ-meson exchange potential vary from author to author, the resultant potentials are only qualitatively the same but quantitatively different.

In Fig.3, the solid curves represent the result obtained by using the σ, δ model[5]. In which $g_\sigma^2/4\pi$ = 6.97, m_σ = 570 MeV, $g_\delta^2/4\pi$ = 0.33, m_δ = 960 MeV, and the phenomenological form factor has the form where m and Q are the mass and momentum of the exchanged meson, respectively, and Λ is a cutoff mass parameter which is taken to be 1414 MeV for both σ and δ meson exchanges. As it is shown in Fig.3, the general feature of the resultant effective two-meson exchange potential is the same as that of the phenomenological potential. Both curves take large negative values at $r \approx 0$, and gradually lead to zero with increasing r. On the other hand, these two curves differ in quantity. Compared with the phenomenological potential, the effective potential curve is much lower in the r < 0.4 fm region, goes to zero much faster in the r > 0.5 fm region, and is distinctly higher in the medium region. This indicates that the medium-range attraction of the former potential is weaker than that of the latter one. Is it possible to obtain the proper phase shift which fits the experimental data with this effective potential? There is no definite answer at this moment and it remains to be further studied. It is noteworthy that the investigation of the N-N scattering phase shift in the quark model has been very revealing. For instance, in Ref.[6], it shows that by taking into account the six-quark components, one only needs a phenomenological potential strength, required by the calculation in the normal nucleon degree of freedom, with a factor of 0.35 to reach good agreement with the experimental data for the scattering phase shift. This indicates that the effect of the six-quark components provides part of the medium-range attractive feature of the nuclear force.

The effective two-meson exchange potential evaluated in this paper is just the portion, corresponding to the contribution from the two-meson exchange in the nucleon-nucleon interaction. Viewing at the quark level, a complete nucleon-nucleon potential should contain the effective one-meson exchange potential via a quark-antiquark pair creation (this part of the interaction and the usual one-meson exchange potential are not quite the same), the Breit-Fermi interaction between two quarks, and the effect of the six-quark states. It is likely that the medium-range attraction provided by the phenomenological σ-meson exchange in the normal meson exchange theory is a synthetical effect from both the six-quark states and the effective two-meson exchange potential.

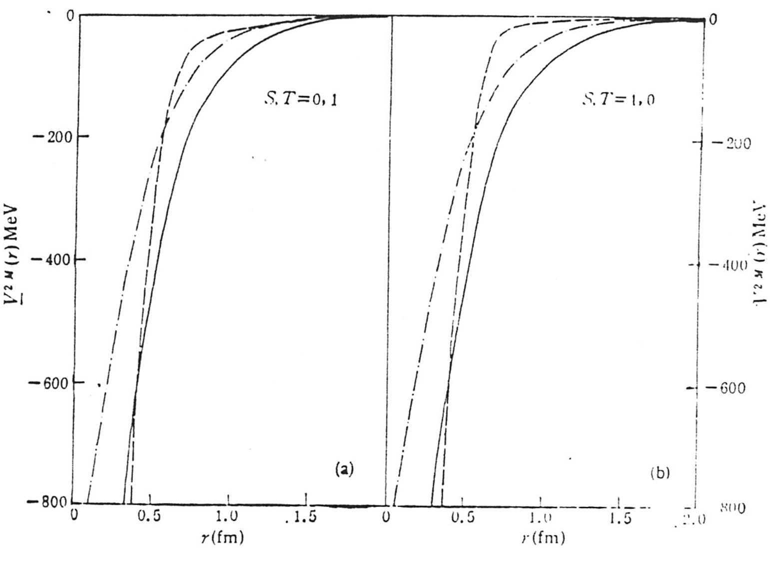

FIG.3 Effective two-meson exchange potential.

Therefore, we cannot expect that the effective two-meson exchange potential given in this work and one of the σ-meson exchange potential will be exactly the same. If we reduce the phenomenological σ-meson exchange potential in Fig.3 by a factor of 2, the medium-range part of the new curve would approach the effective two-meson exchange potential (the new curve is represented by the dotted-dashed curve in Fig.3). The interesting question which deserves further study is: If we employ the complete nucleon-nucleon potential we derived in the quark point of view to study the nucleon-nucleon scattering, can we obtain the N-N scattering phase shift which fits the experimental data very well? Needless to say, it also remains to be answered how to improve the adopted approximation to obtain a better result.

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