Unified Description of *NN* and *YN* Interactions in a Quark Model with Effective Meson-Exchange Potentials

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A simultaneous description of the *NN* and *YN* interactions is attempted in the resonating-group formulation of the spin-flavor SU_6 quark model, in which the full Fermi-Breit interaction with explicit quark-mass dependence acts between quarks, and all the mesons of scalar and pseudoscalar nonets couple directly to quarks. An overall agreement with the existing data is obtained with few adjustable parameters. In the Λp elastic total cross sections, the cusp structure at the ΣN threshold is strongly enhanced by the antisymmetric $LS^{(-)}$ force generated from the Fermi-Breit interaction.

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The understanding of the hyperon-nucleon (*YN*) interaction is important not only for applications to hypernuclear physics [1], but also for elucidating the rich flavor content in low-energy hadron phenomena of the strong interaction. In the quark-model (QM) description, hyperons and nucleons belong to the same class of the spin-flavor SU_6 supermultiplet $\underline{56}$, thus yielding a possible framework for understanding the *YN* interaction on the same level with the *NN* interaction. The composite nature of the nucleon and the hyperon is taken into account most straightforwardly in the resonating-group method (RGM), in which the effective quark-quark interaction is usually built by combining a phenomenological quark-confining potential of simple power-law form with a one-gluon exchange potential through the color analog of the Fermi-Breit (FB) interaction. Since the long-range terms of the interaction are dominated by the meson-exchange effect, any RGM description in the simple $(3q)$-$(3q)$ model must comprise effective meson-exchange potentials (EMEP) introduced by some appropriate means. The Tübingen group [2,3] included a pseudoscalar (PS) meson exchange between the quarks as well as a phenomenological σ-like potential at the baryon level. A microscopic calculation incorporating both PS- and σ-meson exchange potentials acting between the quarks has recently been undertaken by the Salamanca group [4,5] for the *NN* interaction and by the Beijing group for the *YN* and *NN* interactions [6,7]. Although these models reproduce each of the *NN* and *YN* interactions reasonably well, a simultaneous description of these interactions by using an identical set of parameters is still not possible. In the microscopic approach of the EMEP, two points have to be clarified: (i) What difference does the EMEP produce depending on whether it is calculated at the *quark level* or at the *baryon level*? (ii) What is the minimum set of mesons indispensably needed? An advantage of introducing the EMEP at the quark level lies in the stringent relationship of the flavor dependence on various *NN* or *YN* channels, as well as of the relative importance between the direct and exchange terms in the RGM treatment. The utility of introducing the EMEP must, however, be examined by careful analysis against experiment.

In our recent QM study of the *NN* and *YN* interactions [8], we have carried out a detailed analysis of the medium-range central attraction required for a simultaneous description of the *NN*, ΛN, and ΣN interactions. It is found that the attraction for the *YN* systems should be much weaker than that for the *NN* system and that the needed EMEP with this property are conveniently generated from the scalar- (S-) meson nonet exchange in the Nijmegen model-F potential [9]. Furthermore, we have shown that, with only two adjustable parameters determined in the *NN* sector, the model-F meson parameters incorporated into our QM can yield reasonable reproduction of all the low-energy cross-section data of the *YN* systems [10]. This model, called RGM-F, introduces, besides the S-meson nonet, only the tensor component generated from the π- and K-meson exchanges, and uses some approximations in evaluating the spin-flavor factors of the quark-exchange RGM kernel. No vector-meson exchange is invoked in accordance with [11]. The *NN* and *YN* spin-orbit force is generated from the FB interaction as discussed in [8]. One unsatisfactory point in RGM-F is that the strength of the medium-range central attraction of the EMEP has to be chosen differently depending on the spin-flavor exchange symmetry of the two baryons. In this study, we upgrade the EMEP of the RGM-F [10] in two respects. One is to calculate the spin-flavor factors exactly at the quark level, and the other is to include the spin-spin terms originating from all the PS mesons. We show that it is possible to reproduce the available NN and YN data simultaneously in the standard $(3q)$-$(3q)$ formulation, if one assumes the full PS- and S-meson nonet exchanges at the quark level and the flavor symmetry breaking in the quark sector is properly introduced.

Our quark-model Hamiltonian consists of the nonrelativistic kinetic-energy term, the quadratic confinement potential, the full FB interaction with explicit quark-mass dependence, and the S- and PS-meson exchange potentials acting between quarks,

$$H = \sum_{i=1}^{6}\left(m_i c^2 + \frac{\boldsymbol{p}_i^2}{2m_i}\right) + \sum_{i<j}^{6}\left(U_{ij}^{\mathrm{Cf}} + U_{ij}^{\mathrm{FB}} + \sum_{\beta} U_{ij}^{\mathrm{S}\beta} + \sum_{\beta} U_{ij}^{\mathrm{PS}\beta}\right).$$

The confinement potential of quadratic power law gives a vanishing contribution to the interaction in the present formalism. As is discussed in Refs. [8,10], it is important for a realistic description of the interaction to treat the Galilean noninvariant terms of U^{FB} carefully and restore the empirical reduced mass of the YN system in the RGM framework. The EMEP's, $U^{\mathrm{S}\beta}$ and $U^{\mathrm{PS}\beta}$, are constructed from the quark-meson vertex Lagrangian in the standard procedure to derive one-boson exchange potentials (OBEP) for S and PS mesons. As to the interaction components and the meson species β, we introduce the central part of ϵ, S^*, δ, and κ of the S-meson nonet, and the spin-spin and tensor terms of the η', η, π, and K of the PS-meson nonet. The scalar meson masses are chosen to be 800, 1250, 970, and 1145 MeV, respectively, while the empirical meson masses are used for PS mesons. Although one may think that the ϵ mass is a little too large, the NN fit with almost equal quality can be obtained with a smaller value of 760 MeV [9]. The nucleon and hyperon are described by a simple $(0s)^3$ harmonic-oscillator wave function with a common width parameter b, which yields a Gaussian form factor $F(\boldsymbol{q}) = \exp\{-(b\boldsymbol{q})^2/6\}$ for these baryons. It should be noted that the direct term of the RGM equation is composed of the standard OBEP with the Gaussian form factor. The SU_3 coupling constants, f_1 and f_8, at the baryon level are related to the quark-meson coupling constants involved in the original quark-meson vertex Lagrangian through simple numerical factors. Table I lists these SU_3 parameters, which could be compared with those of the Nijmegen soft-core potentials given in Table VI of Ref. [12]. The value of $f_8/\sqrt{4\pi}$ in Table I, when combined with the form factor, is chosen to reproduce $f_{NN\pi}/\sqrt{4\pi} = 0.278\,43$ [9] for point nucleons, assuring the asymptotic behavior of the one-pion exchange potential (OPEP). The mixing of the flavor singlet octet mesons, which can equivalently be introduced at the quark level, is specified by the angle θ.

TABLE I. The SU_3 coupling constants, f_1 and f_8, and the mixing parameter, θ, for the scalar (S) and pseudoscalar (PS) mesons in the direct term. The value of θ is changed to 65° for the S mesons in the $\Sigma N(I = 3/2)$ channel. See text.

	$f_1/\sqrt{4\pi}$	$f_8/\sqrt{4\pi}$	θ
S	2.891 38	1.075 09	27.78°
PS	0.214 26	0.269 94	−23°

Another SU_3 parameter, the $F/(F + D)$ ratio α, of the OBEP models is no longer a free parameter, but takes the pure SU_6 value (i.e., 1 for the S mesons and 2/5 for the PS mesons) in the present model with exact SU_6 spin-flavor functions.

The spin-spin term of the π exchange is particularly important to reproduce the low-energy behavior of the NN $^1S_0$ phase shift as well as the higher partial waves, while the η, η', and δ mesons play the essential role in correcting the well-known imbalance of the NN ^1S and ^3S central QM potentials [8]. We do not ignore the δ-function type contact term contained in the spin-spin term of the PS mesons, but rather introduce it with a single reduction factor c_δ, which is chosen to be $c_\delta = 0.381$ for all channels. Furthermore, we find that the ratio $\alpha = 1$ of pure electric type for the S mesons is too rigid to retain a well-balanced central attraction of the ΛN and ΣN systems. We avoid this difficulty by modifying the mixing angle of the S mesons only for the $\Sigma N(I = 3/2)$ channel $[\theta(I = 3/2) = 65°]$, which would, otherwise, be too attractive compared with the other YN channels.

In addition to the SU_3 parameters given in Table I, the optimum QM parameters are also searched to fit the NN S-wave and P-wave phase shifts under the constraint that the deuteron binding energy and the np $^1S_0$ scattering length are reproduced. Their final values are

$$b = 0.616 \text{ fm}, \quad m_{ud}c^2 = 360 \text{ MeV}, \quad \alpha_S = 2.1742, \quad \text{and} \quad \lambda = m_s/m_{ud} = 1.526\,.$$

Here the mass ratio λ controls the flavor symmetry breaking in the quark sector, and it is treated as one of the free parameters to fit the low-energy YN cross-section data and the Λ-Σ mass difference of 77.49 MeV. Since the quadratic confinement potential does not contribute to the baryon-baryon interaction, one can choose any arbitrary value for the strength of the confinement potential a_c. If we fit the absolute value of the nucleon mass with this parameter, the Λ and Σ rest masses are calculated to be 1158 and 1236 MeV, respectively, which are about 40 MeV higher than the empirical masses.

Figures 1 and 2 compare the calculated NN S- and P-wave phase shifts to the most recent phase-shift analysis by the Nijmegen group [13]. The $^1P_1$ phase shift and the low-energy behavior of the $^1S_0$ phase shift demonstrate remarkable improvement over the previous RGM-F result [10], due to the correct treatment of the long-range OPEP tail in the spin-spin term. Because

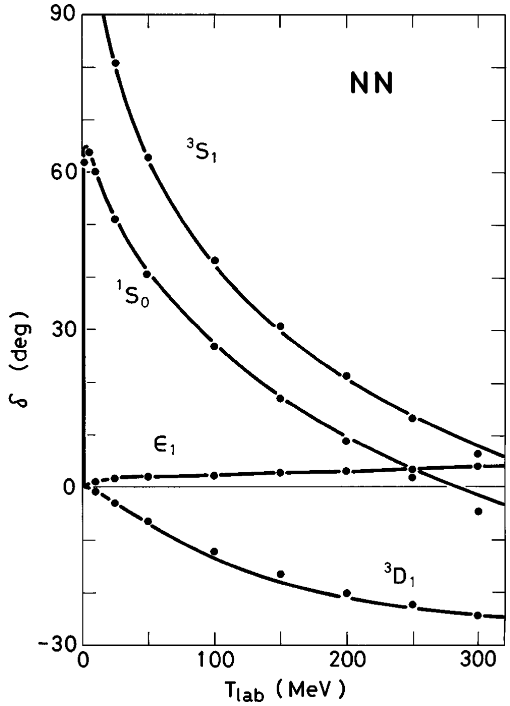

FIG. 1. Calculated NN $^3S_1$, $^3D_1$, and $^1S_0$ (bar) phase shifts, and the $^3S_1$-$^3D_1$ mixing parameter ϵ_1 cpuompared with the phase shift analysis by Stoks *et al.* [13].

of the same reason, the phase shifts of higher partial waves are also reproduced within the accuracy of 1° to 2° at $T_{\rm lab} = 300$ MeV, except for the $^3D_2$ phase shift. The overestimation of this particular phase shift is 6° at $T_{\rm lab} = 150$ MeV and 12° at $T_{\rm lab} = 300$ MeV, which indicates that the tensor and quadratic spin-orbit components originating from the FB tensor interaction are too small. The quadruple moment of the deuteron is given by $Q = 0.284$ fm^2 ($Q_{\rm exp} = 0.2860 \pm 0.0015$ fm^2) with the D-state probability $P_D = 5.88\%$. The np effective-range parameters are all well reproduced; $a_t = 5.41$ fm, $r_t = 1.76$ fm, $a_s = -23.62$ fm, and $r_s = 2.61$ fm. Although the fit to the NN data is still not as good as that of the OBEP approach, the agreement is satisfactory, at least for the purpose of extending the present model to the YN interaction. The low-energy scattering and reaction "total" cross sections for Σ^+p and Σ^-p channels are compared in Fig. 3 with the experimental data [14,15] and with the theory of Ref. [6]. The Coulomb force is treated as described in [10]. The improvement over the RGM-F result [10], especially in the Σ^-p elastic cross sections, is an outcome of the weaker central attraction of the $\Sigma N(I = 1/2)$ channel in the present model. On the other hand, the agreement of the $\Sigma^-p \to \Lambda n$ reaction cross sections becomes a little worse. We have also examined the Σ^+p scattering total cross sections in higher energies ($p_\Sigma = 400$–600 MeV/c) and confirmed the RGM-F conclusion [8,10] that they show no bump structure in contrast to the Nijmegen hard-core model [9]. We show in Fig. 4 the Λp elastic total cross sections obtained by solving the ΛN and $\Sigma N(I = 1/2)$ coupled-channel RGM equation. Since the threshold energy of the ΣN channel is properly reproduced, a cusp structure of the ΛN $^3S_1$ state appears at the incident momentum of $p_\Lambda = 638$ MeV/c. The bump structure, predicted by the RGM-F calculation [10] just below the ΣN threshold, now spreads out over

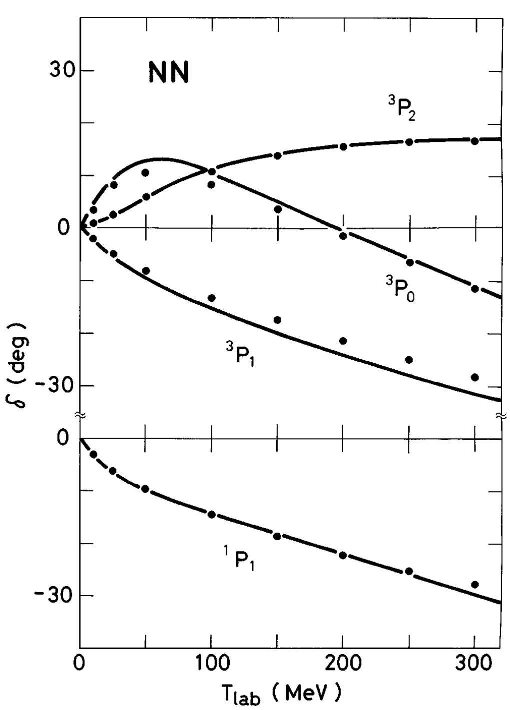

FIG. 2. The same as Fig. 1, but for ^3P_J ($J = 0, 1, 2$) and $^1P_1$ channels.

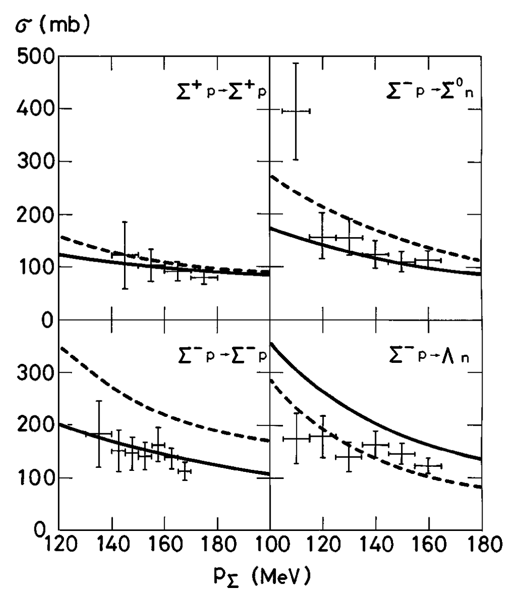

FIG. 3. Calculated Σ^+p and Σ^-p elastic and charge-exchange "total" cross sections compared with the experimental data [14,15] and with the theoretical calculation of Zhang *et al.* [6] (dashed curves).

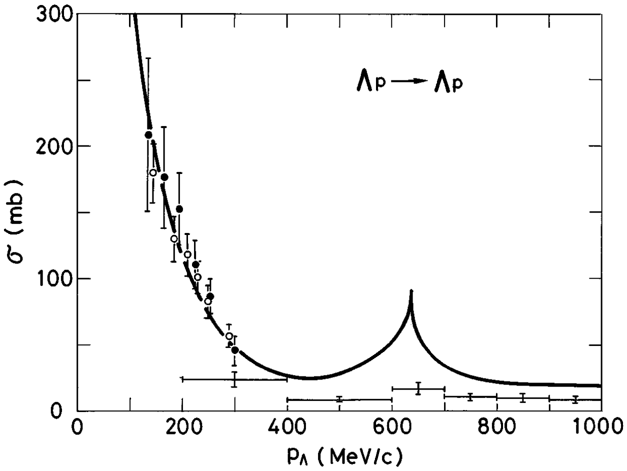

FIG. 4. Calculated Λp elastic total cross sections compared with the experimental data of Refs. [16–18] (full circles, open circles, and no circles, respectively).

the very wide energy region of $p_\Lambda = 400-1000$ MeV$/c$, and enhances the cusp structure by almost a factor of 2 in magnitude. This is the consequence of the P-wave channel-coupling effect with the $\Sigma N(I = 1/2)$ channel due to the antisymmetric $LS^{(-)}$ force. Since this force originates entirely from the FB interaction, experimental confirmation of the enhanced cusp structure is of great interest in establishing the role of the $LS^{(-)}$ force.

In summary, we have shown that a simultaneous description of the NN and YN interactions is possible in the standard $(3q)$-$(3q)$ RGM, if the full Fermi-Breit interaction with the explicit flavor symmetry breaking is augmented with the effective meson-exchange potentials including the central, spin-spin, and tensor components generated from all the mesons of the scalar and pseudoscalar nonets. These effective meson-exchange potentials are calculated microscopically at the quark level. We have invoked no exotic mechanism to correct the well-known imbalance of the NN ^1S and ^3S quark-model potentials, but paid heed to the role of the η, η', and δ mesons. Although further investigations on the roles of mesons, including the vector mesons, are still necessary, the quality of the overall fit in the present calculation shows that the microscopic quark model is promising to correlate various data for the NN and YN systems. It is predicted that the $\Sigma^+ p$ and Λp elastic total cross sections show different energy dependence from other models. Experimental confirmation of these will be one of the interesting subjects in the near future. An extension to the system of strangeness $S = -2$ is straightforward and its study is in progress.

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