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HYPERON-NUCLEON INTERACTION IN THE SU$_6$ QUARK MODEL †‡

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Abstract

A unified description of the hyperon-nucleon interaction consistent with the NN interaction is made posssible, if the SU_6 quark model which incorporates the full Fermi-Breit interaction with explicit flavor symmetry breaking is augmented with minimum effective meson exchange potentials induced from the scalar-meson central attraction and π, K tensor force of the Nijmegen model-F potential. With a few strength parameters determined from the deuteron binding energy and NN $^1S_0$ phase shift, all the low-energy cross sections of the hyperon-nucleon interaction currently available are reasonably reproduced in a unified RGM framework for the B_8-B_8 interaction.

1. Introduction

In spite of the basic importance in the study of hypernuclei, our present understanding of the hyperon-nucleon (YN) interaction is quite unsatisfactory in the sense that many different versions of the one boson exchange potentials (OBEP) are not discriminated due to the scarce experimental information.[1] Since hyperons and nucleons belong to the same class of the spin-flavor SU_6 supermultiplet $\underline{56}$ in the quark model, it will provide a possible framework to understand the YN interaction and the nucleon-nucleon (NN) interaction in a unified way. We have recently constructed a unified model for the NN and YN interactions in terms of the SU_6 quark model with a minimum augmentation of effective meson exchange potentials. As to the basic idea for applying the RGM framework to quark-hadron problems, ref. 2 should be referred to. The model, which we call RGM-F, incorporates the full Fermi-Breit (FB) interaction of the colored quark-gluon interaction Lagrangian in the one-gluon exchange approximation. The flavor symmetry breaking (FSB) of the kinetic-energy term and the FB interaction is explicitly introduced through the mass difference of up-down and strange quarks without any approximation. Besides the well-known short-range repulsion due to the color-magnetic interaction and the Pauli principle, the spin-dependent central, LS, and the short-range tensor forces are nicely described in this simple framework.[3] However, since the very important medium-range attraction and the long-range tensor force are never described by any of the quark model, the RGM-F introduces the central force of the scalar-meson exchange potentials and the π, K tensor force acting between quarks. The space-spin parts of the exchange kernels for these effective meson exchange potentials are explicitly calculated.

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2. Features of the Central Attraction for the YN Interaction

As a system of two unidentical octet baryons, the YN interaction has several new features which are not shared with the NN system. We employ a generalized Pauli principle in the flavor SU_3 space, and classify YN systems according to the flavor symmetry $\mathcal{P}$. (See, for example, table I of ref. 4.) If the quark Hamiltonian were completely flavor singlet, some configurations such as ${}^1E$ or ${}^3O$ states of $\Sigma N(I = 3/2)$ and $NN(I = 1)$ systems, which belong to the same SU_3 state $(\lambda\mu) = (22)$, would yield an identical potential and the same values of phase shifts. Another example is seen for the flavor-antisymmetric channel ($\mathcal{P} = a$) in ΛN and $\Sigma N(I = 1/2)$ systems. This feature is, in fact, approximately observed even in the OBEP, in which the meson-baryon coupling constants are constrained by the SU_3 relations and the flavor symmetry is explicitly broken only through the hadron masses and possibly hard-core radii.

In order to see this feature more carefully, we show in tabel 1 the phase shift behavior of the most successful Nijmegen potential, when the noncentral forces are turned off. From this table, we can find that there is a strong correlation between the values of X_N and attractive or repulsive nature of the phase-shift behavior. Namely, for each group of the eight S-wave or P-wave phase shifts, the larger X_N indicates the stronger attraction and the negative X_N values lead to the negative (or less attractive) phase shifts. This can be confirmed by solving a simlified RGM equation which retains only the kinetic-energy exchange kernels. In other words, the gross feature of the phase-shift behavior is already reproduced if the Pauli principle is taken into account. An important point here is that the spin-flavor factors for the normalization kernels are specified only by the SU_3 contents of the two-baryon system, and the essential features of the central phase shifts are mainly determined by the Pauli principle, the color-magetic interaction, and an almost flavor-independent central attraction.

Apparently, this nice feature of the flavor SU_3 symmetry is related to the basic fact that gluons do not have any flavor degree of freedom. The nice correspondence between X_N and the flavor dependence of the Nijmegen model-D in table 1 is, however, somehow artificial, since the hard-core radii in this model are determined for each of the NN and YN particle channels. On the other hand, the core-radii of the model-F are determined for each SU_3 state, which is much closer to the quark-model description. Consequently, the quark-model study of the central force in the YN interaction is essentially the study of FSB not only in the quark sector, but also in the effective meson-exchange attraction.

Table 1 Phase-shift behavior of the Nijmegen model-D central potentials and its correlation with the spin-flavor factors, X_N, of the quark-exchange normalization kernels.

$B_1\ B_2$	$\mathcal{P} = s$				$\mathcal{P} = a$			
	${}^1S$	X_N	${}^3P$	X_N	${}^3S$	X_N	${}^1P$	X_N
NN	$< 60°$	$\frac{1}{9}$	weak repulsion	$-\frac{31}{27}$	$< 18°$	$\frac{1}{9}$	repulsion	$-\frac{7}{3}$
ΛN	$< 22°$	0	$\leq 2°$ →repulsion	-1	$< 16°$	0	$\leq 3°$	-1
$\Sigma N(\frac{1}{2})$	strong repulsion	$-\frac{8}{9}$	$< 16°$	$\frac{5}{27}$	$< 15°$	0	~0 →attraction	-1
$\Sigma N(\frac{3}{2})$	$< 38°$	$\frac{1}{9}$	~0 →repulsion	$-\frac{31}{27}$	strong repulsion	$-\frac{7}{9}$	$< 76°$	$\frac{1}{3}$

From this simple analysis, we can conclude that the introduction of the constant (flavor singlet) attraction in the simple (3q)-(3q) model is never successful, as long as the FSB is properly introduced in the quark sector. For example, if the FSB is introduced in the reduced mass and the repulsive color-magnetic interaction in $\Sigma N(I = 3/2)\ ^1S$ channel, it turns out to be more attractive than $NN(I = 1)\ ^1S$ channel, and the feature in table 1 will never be reproduced. We should, therefore, obliged to use less attractive scalar-meson exchange potentials for ΣN and ΛN channels than that for NN.

In RGM-F, we employ the scalar-meson nonet of the Nijmegen model-F with the singlet-octet meson mixing. The products of the two coupling constants are evaluated at the baryon level and are assumed to be the same as the original values of the Nijmegen model-F, so that the direct potential of the RGM equation turns out to be the real Nijmegen potential with the Gaussian form factor corresponding to the harmonic-oscillator size parameter b (=0.6 fm) of the (3q) clusters. Owing to the appropriate reduction of attractions from NN to ΛN and ΣN, we only need to introduce a common reduction factor c for each of the flavor states. These are determined to be

$$c = 0.4212 \text{ for } \mathcal{P} = a\ (^3E \text{ or } ^1O)\ ,$$
$$c = 0.56 \text{ for } \mathcal{P} = s\ (^1E \text{ or } ^3O)\ ,$$

such that the deuteron binding energy and the $^1S_0$ phase shift for the NN system are reproduced, respectively. Since the quark parameters are fixed to the standard values ($m_{ud}c^2 = 313\ MeV$ and α_S from the correct $\Delta - N$ mass splitting), only $\lambda = m_s/m_{ud}$ (the ratio for strange to up-down quark masses) is a remaining free parameter, while it is fixed to $\lambda = 1.25$ for the time being. In Fig. 1, the $^1S_0$ phase shifts for all the NN and YN channels are shown. One finds that the magnitude of the central attraction is well controlled with the above prescription.

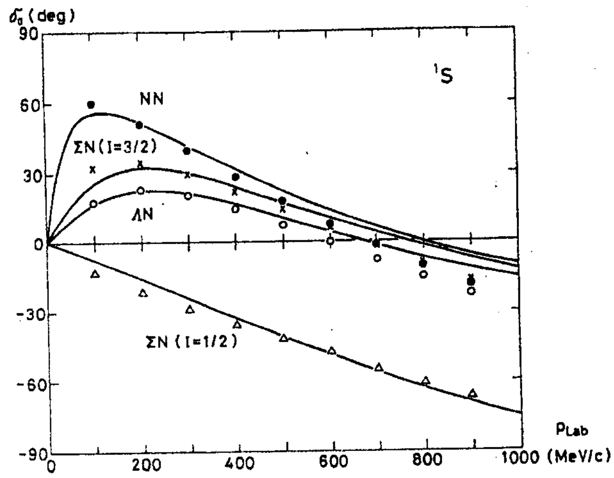

Fig. 1 Calculated $^1S_0$ phase shifts compared with those of Nijmegen model-F.[4]

3. Noncentral Forces and the Phase Shift Behavior

For the triplet states, the effect of noncentral forces are important. In the YN interaction, however, the total spin is no longer a conserved quantity as a result of the rich flavor structure, and the so-called antisymmetric LS force ($LS^{(-)}$) causes the simultaneous spin and flavor-symmetry flip in the YN system. Since these LS forces and the short range tensor force is correctly reproduced from the FB interaction,[3] only the π and K tensor

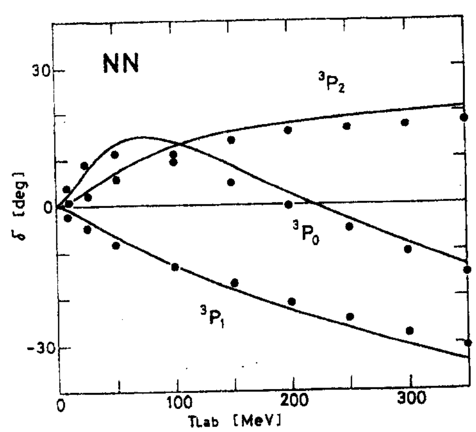

Fig. 2 Calculated $NN\ ^3P_J$ phase shifts compared with the most recent phase shft analysis.[5]

forces are introduced in RGM-F in a similar way to the central force of the scalar-mesons, but this time with no reduction factors. Figure 2 shows the NN phase shifts for ^3P_J states, which are already one of the model predictions, since c is determined in the $^1S_0$ channel of the NN system. In the single-(cluster) channel calculation of the NN and $\Sigma N(I = 3/2)$ systems, a major difference of the phase shift behaviors in RGM-F and the Nijmegen potentials is only in the $^1P_1$ state of the $\Sigma N(I = 3/2)$ system.

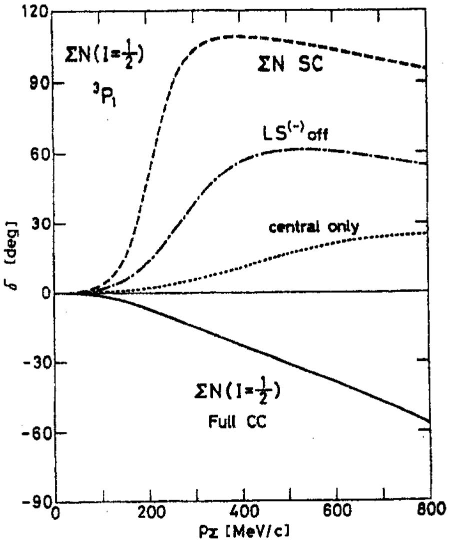

Fig. 3 $\Sigma N(I = 1/2)\, ^3P_1$ phase shifts in various approximations. See the text for the explanation.

For Λ-$\Sigma(I = 1/2)$ coupled-channel problem, we have further complications arising from how to handle the meson-exchange potentials in the coupled-channel RGM formalism. The basic idea is to extend the prescription of the single-channel calculation and formulate it such that it reproduces the correct coupling potentials in the direct potential after the folding of the effective meson exchange potentials between quarks with the $(3q)$ cluster wave functions. The detailes will be publised elsewhere. The coupling of the ΛN and ΣN channels is not so strong as long as $^1S_0$ state is concerned. However, this is not true anymore, once the tensor and $LS^{(-)}$ forces are involved. The $^3S_1$ phase shift in the ΛN channel shows a sharp step-like resonance whose main component dwells in the $\Lambda N\ ^3D_1$ channel, due to the cooperative role of the ΛN-ΣN transition and the tensor force. Similarly, $LS^{(-)}$ force is very important in the $^3P_1$ states of the ΛN-ΣN coupling problem. Figure 3 shows the interesting change of the $\Sigma N(I = 1/2)\ ^3P_1$ phase shift, with the successive introduction of various effects. When only the central force is introduced, the phase shift rise is not so great. Once the $LS^{(-)}$ force is introduced, the attractive effect of the LS and tensor forces are largely enhanced through the coupling with the $^1P_1$ channel of the $\Sigma N(I = 1/2)$ system. Further extension of the model space through the coupling with the ΛN channel suddenly moves this resonance to the ΛN channel, where very prominent broad step-like resonance is observed. This interesting effect of $LS^{(-)}$ force in the ΛN-ΣN coupled-channel problem is not introduced in the Nijmegen model.

4. Total Cross Sections

The total nuclear cross sections for YN elastic scattering and reactions predicted in RGM-F are shown in Figs. 4 - 8. In calculating these cross sections, the Coulomb effect is entirely neglected and the standard SU_2 relations are employed to generate the scattering amplitudes in the particle basis. Although Σ^-p elastic cross sections in Fig. 6 overestimates more than 40 %, the agreement with the scarce experimental data is reasonable, considering that these are essentially no-parameter calculations since the two values for c are determined in

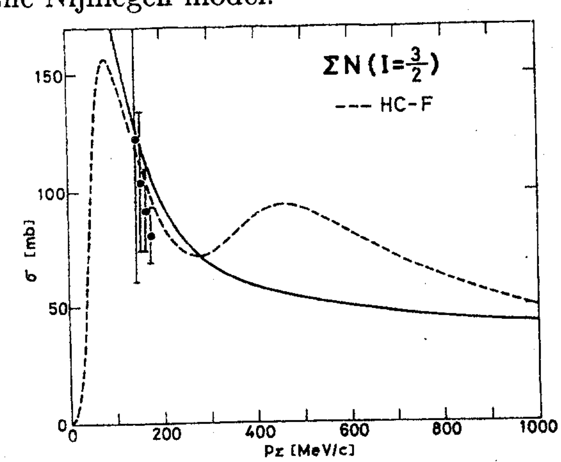

Fig. 4 Calculated Σ^+p total elastic nuclear cross section compared with that of Nijmegen model-F (dashed curve).[4] The data is taken from ref. 6.

the NN sector. The difference of the RGM-F result and the prediction of the Nijmegen model in Σ^+p system in Fig. 4 is due to the different phase shift behavior of the $^1P_1$ state. The big bump in the ΛN cross section around $p_\Lambda = 300 - 500MeV$ is due to the effect of $LS^{(-)}$ force discussed above. Further improvement of the experimental data will help us understand these phenomena.

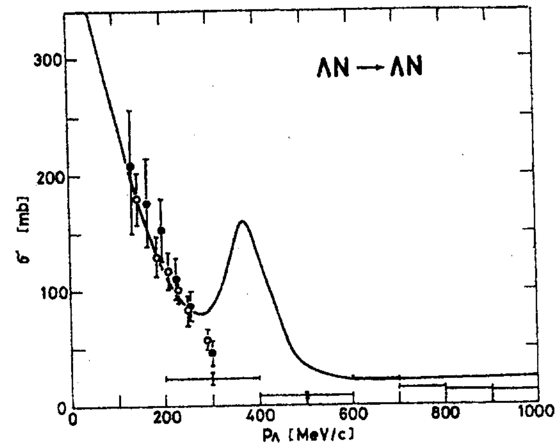

Fig. 5 Calculated ΛN total elastic nuclear cross section compared with the data.[7]

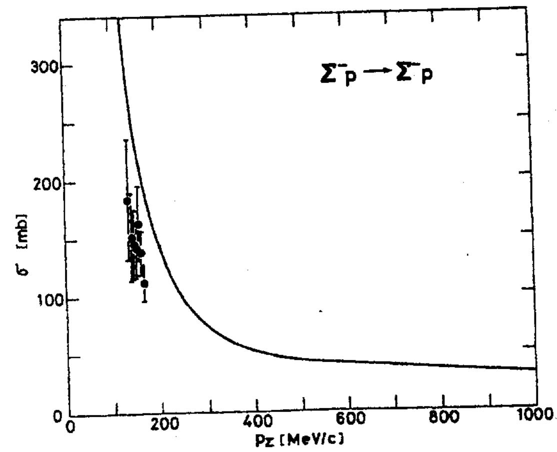

Fig. 6 Calculated Σ^-p total elastic nuclear cross section compared with the data.[8]

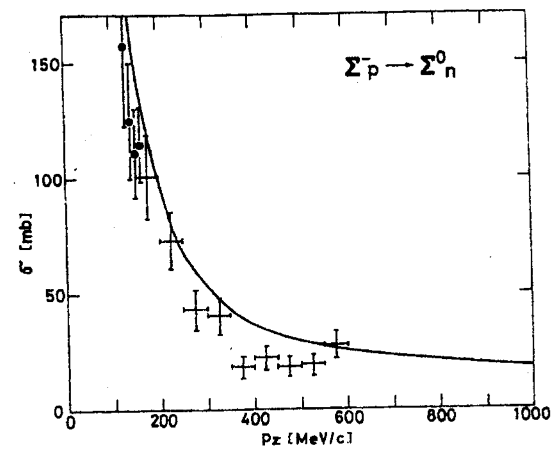

Fig. 7 Calculated $\Sigma^-p \to \Sigma^0 n$ charge exchange total reaction cross section compared with the data.[8,9]

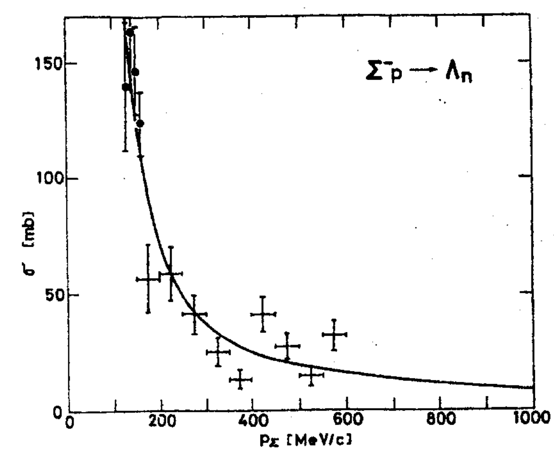

Fig. 8 Calculated $\Sigma^-p \to \Lambda n$ total reaction cross section compared with the data.[8,9]

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