# A Realistic Description of Nucleon-Nucleon and Hyperon-Nucleon Interactions in the $SU_6$ Quark Model*

Y. Fujiwara[1**], M. Kohno[2], C. Nakamoto[3] and Y. Suzuki[4]

[1]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[2]Physics Division, Kyushu Dental College, Kitakyushu 803-8580, Japan
[3]Suzuka National College of Technology, Suzuka 510-0294, Japan
[4]Department of Physics, Niigata University, Niigata 950-2181, Japan

**Abstract.** The $SU_6$ quark model for the $NN$ and $YN$ interactions, developed by the Kyoto-Niigata group, is upgraded to incorporate some effects of scalar and vector mesons exchanged between quarks. The phase-shift agreement in the $NN$ sector at the non-relativistic energies up to $T_{\rm lab} = 350$ MeV is greatly improved. The essential feature of the $\Lambda N$-$\Sigma N$ coupling is qualitatively similar to that obtained from the previous models. The $G$-matrix calculation of the $\Lambda N$-$\Sigma N$ coupled-channel system shows that the $\Sigma$ single-particle potential is repulsive in ordinary nuclear matter. The single-particle spin-orbit strength for the $\Lambda$ particle is found to be very small, in comparison with that of the nucleons.

The quark-model study of the nucleon-nucleon ($NN$) and hyperon-nucleon ($YN$) interactions is motivated to gain a natural and accurate understanding of the fundamental strong interaction, in which the quark-gluon degree of freedom is believed to be the most economical ingredient to describe the short-range part of the interaction, while the medium- and long-range parts are dominated by the meson-exchange processes. We have recently achieved a simultaneous and realistic description of the $NN$ and $YN$ interactions in the resonating-group (RGM) formalism of the spin-flavor $SU_6$ quark model. [1–3] In this approach the effective quark-quark interaction is built by combining a phenomenological quark-confining potential and the colored version of the Fermi-Breit (FB) interaction with minimum effective meson-exchange potentials (EMEP) of scalar and pseudo-scalar meson nonets directly coupled to quarks. The flavor symmetry breaking for the $YN$ system is explicitly introduced through the quark-mass dependence of the Hamiltonian. An advantage of introducing the EMEP at the quark level lies in the stringent relationship of the flavor dependence appearing in the various $NN$ and $YN$ interaction pieces. In this way we can utilize our rich knowledge of the $NN$ interaction to minimize the ambiguity of model parameters, which is crucial since the present experimental data for the $YN$ interaction are still very scarce.

In this report we upgrade our model to incorporate vector mesons and the momentum-dependent Bryan-Scott terms, and compare the $NN$ and $YN$ observables with the existing experimental data. This model is dubbed fss2 since it is based on our previous model FSS [2,3] The agreement to the phase-shift parameters in the $NN$ sector is greatly improved. The model fss2 shares the good reproduction of the $YN$ scattering data and the essential features of the $\Lambda N$-$\Sigma N$ coupling with our previous models [1–3]. The single-particle (s.p.) potentials of $N$, $\Lambda$ and $\Sigma$ are predicted through the $G$-matrix calculation, which employs the quark-exchange kernel explicitly. [4] The strength of the s.p. spin-orbit potential is also examined by using these $G$-matrices. [5] These applications of fss2 are discussed by Kohno in the present symposium.

A new version of our quark model is generated from the Hamiltonian which consists of some extra pieces of interaction generated from the scalar (S), pseudoscalar (PS) and vector (V) meson-exchange potentials acting between quarks:

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

* Talk delivered by Y. Fujiwara at the workshop on *Few-Quark Problems* in Bled, Slovenia, July 8–16, 2000.
** E-mail: fujiwara@ruby.scphys.kyoto-u.ac.jp

It is important to include the momentum-dependent Bryan-Scott term in the S- and V-meson contributions, in order to ensure the correct asymptotic behavior of the s.p. potentials in high-momentum region. [6] We have calculated $U_N(q_1)$ by using the so-called $t^{eff}\rho$ prescription and made sure that it turns into repulsive beyond the incident momentum $q_1 \sim 6$ fm$^{-1}$, while our old model FSS is too attractive, having the minimum value $\sim -70$ MeV around $q_1 \sim 10$ fm$^{-1}$. Another important feature of fss2 is the introduction of vector mesons for improving the fit to the phase-shift parameters in the $NN$ sector. Since the dominant effect of the $\omega$-meson repulsion and the $LS$ components of $\rho$, $\omega$ and $K^*$ mesons are already accounted for by the FB interaction, only the quadratic $LS$ ($QLS$) component of the octet mesons is expected to play an important role to cancel partially the strong one-pion tensor force. Further details of the model fss2 is given in [7]. The model parameters are determined by fitting the most recent result of the phase shift analysis, SP99 [8], for the $np$ scattering with the partial waves $J \leq 2$ and the incident energies $T_{\rm lab} \leq 350$ MeV, under the constraint of the deuteron binding energy and the $^1S_0$ $NN$ scattering length, as well as the low-energy $YN$ total cross sections. The deuteron $D$-state probability of fss2 is 5.5 %, which is slightly smaller than 5.88 % in FSS [2].

Figure 1 shows some important low-partial wave $NN$ phase-shift parameters, compared with the experiment SP99. The previous result by FSS is also shown with the dotted curves. The $^3D_2$ phase shift is greatly improved by the $QLS$ component. The good accuracy of the $NN$ phase-shift parameters continues up to $T_{\rm lab} \sim 600$ MeV, where the inelasticity of the $S$-matrix becomes appreciable.

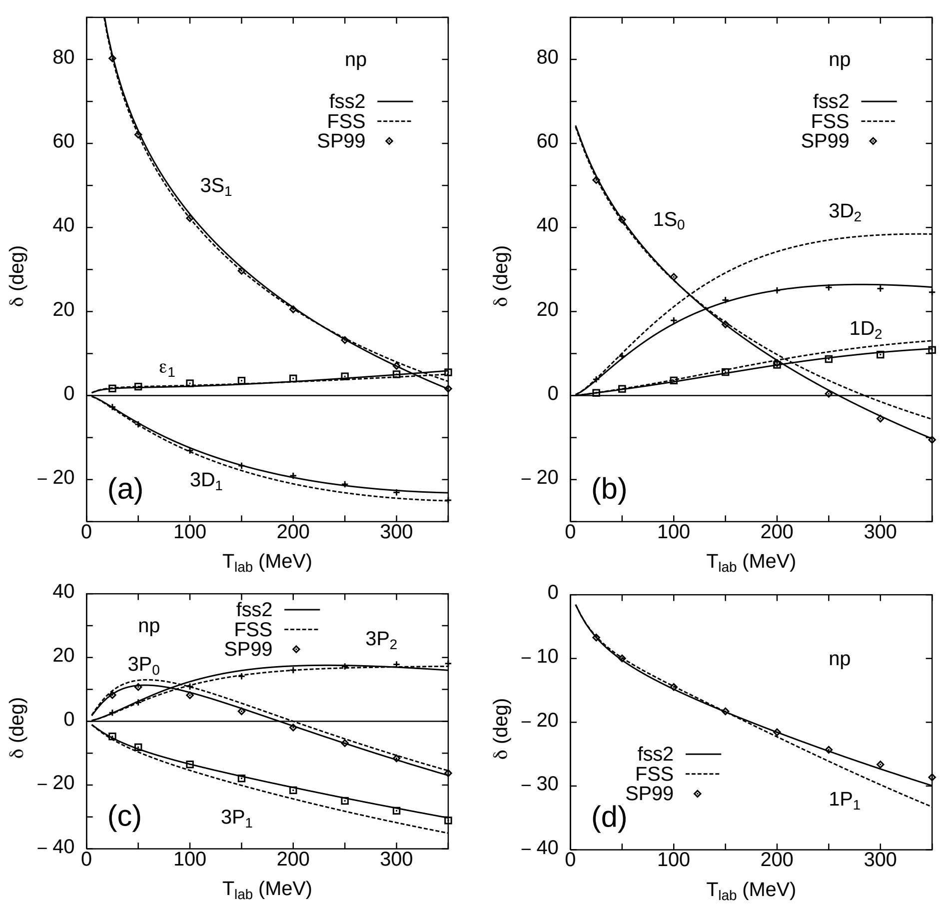


**Fig. 1.** Comparison of $np$ phase shifts with the phase-shift analysis SP99 by Arndt *et al.* The dotted curves are by FSS.

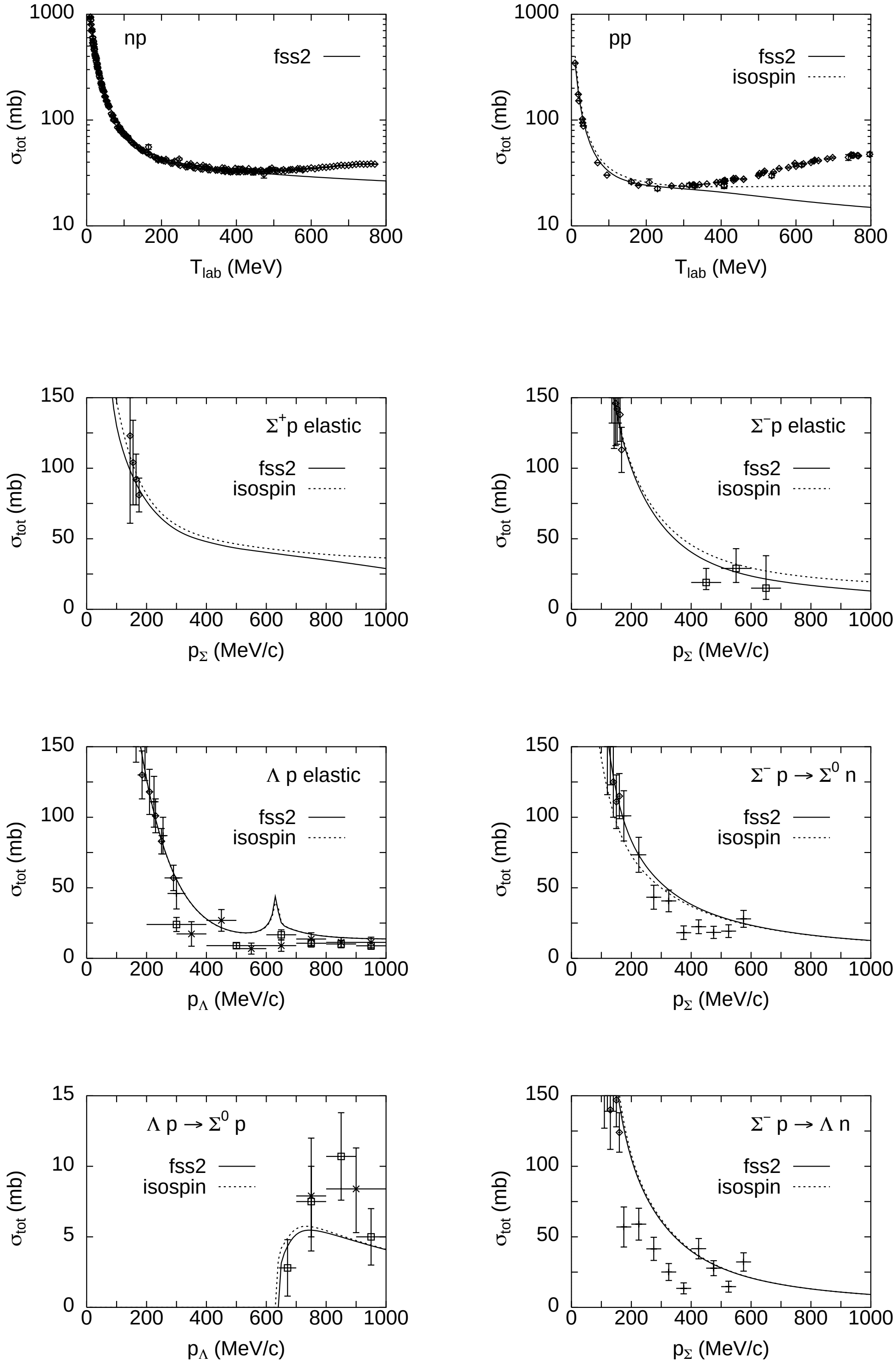


**Fig. 2.** Calculated $NN$ and $YN$ total cross sections compared with the available experimental data.

The total cross sections of the $NN$ and $YN$ scattering predicted by fss2 are compared with the available experimental data in Fig. 2. The "total" cross sections for the scattering of charged particles (i.e., $pp$, $\Sigma^+p$ and $\Sigma^-p$ systems) are calculated by integrating the differential cross sections over $\cos\theta_{\rm min} = 0.5 \sim \cos\theta_{\rm max} = -0.5$. The solid curves indicate the result in the particle basis, while the dashed curves in the isospin basis. In the latter case, the effects of the charge symmetry breaking, such as the Coulomb effect and the small difference of the threshold energies for $\Sigma^-p$ and $\Sigma^0n$ channels, are neglected. The empirical total cross sections for the $np$ and $pp$ systems include the inelastic cross sections. This is the reason why our result with no inelasticity underestimate these total cross sections above the pion threshold. If we properly compare the total elastic cross sections with an appropriate angular range, we find that the agreement with the experiment is excellently good up to $T_{\rm lab} = 800$ MeV. We find that the cusp structure of the $\Lambda p$ total cross sections at the $\Sigma N$ threshold is enhanced by the effect of the $P$-wave $\Lambda N$-$\Sigma N$ coupling due to the antisymmetric spin-orbit force ($LS^{(-)}$ force), which is a new feature of the $YN$ interaction as the scattering of non-identical particles. In the present model fss2, the $\Sigma N(I = 1/2)$ ${}^3P_1$ resonance still stays at the $\Sigma N$ channel, which is similar to the situation in RGM-H [2]. As to the $\Lambda N$-$\Sigma N$ coupling in the positive-parity states, the present ${}^3S_1$-${}^3D_1$ tensor coupling by the one-pion tensor force is rather close to that in RGM-F [1]. The $\Sigma^-p$ inelastic capture ratio at rest is $r_R = 0.442$ in fss2, which is slightly smaller than the recent empirical values ${r_R}^{\rm exp} = 0.474 \pm 0.016$ and $0.465 \pm 0.011$ [9,10].

In summary, We have upgraded our quark model FSS to fss2, by incorporating the momentum-dependent Bryan-Scott term and the vector-meson exchange potential acting between quarks. With a few phenomenological ingredients, the accuracy of the model in the $NN$ sector has now become almost comparable to that of the OBEP models. The existing data for the $YN$ scattering are well reproduced and the essential feature of the $\Lambda N$-$\Sigma N$ coupling is almost unchanged from our previous models. [1,2] We also calculated $NN$ and $YN$ $G$-matrices in ordinary nuclear matter, by solving the Bethe-Goldstone equations for the quark-exchange kernel. Similar to our previous models, fss2 predicts a repulsive $\Sigma$ s.p. potential, the strength of which is about 10 MeV. The repulsive isoscalar part of the $\Sigma$ s.p. potential is reported to be compatible with recent BNL $(K^-, \pi^\pm)$ data [11]. The relative ratio of the Scheerbaum factors for $\Lambda$ to $N$ is about 1/5 in fss2, due to the strong effect of $LS^{(-)}$ force and the effect of the flavor symmetry breaking. It can be further reduced by many-body effects such as the starting-energy dependence and the density dependence of the $G$-matrix. This small spin-orbit potential for the $\Lambda$ might be confirmed in future experiments.

## References

1. Y. Fujiwara, C. Nakamoto and Y. Suzuki, Prog. Theor. Phys. **94** (1995) 215, 353.
2. Y. Fujiwara, C. Nakamoto and Y. Suzuki, Phys. Rev. Lett. **76** (1996) 2242; Phys. Rev. **C54** (1996) 2180.
3. T. Fujita, Y. Fujiwara, C. Nakamoto and Y. Suzuki, Prog. Theor. Phys. **100** (1998), 931.
4. M. Kohno, Y. Fujiwara, T. Fujita, C. Nakamoto and Y. Suzuki, Nucl. Phys. **A674** (2000), 229.
5. Y. Fujiwara, M. Kohno, T. Fujita, C. Nakamoto and Y. Suzuki, Nucl. Phys. **A674** (2000), 493.
6. Y. Fujiwara, M. Kohno, C. Nakamoto and Y. Suzuki, Theor. Phys. **103** (2000), 755.
7. Y. Fujiwara, M. Kohno, C. Nakamoto and Y. Suzuki, The electric proceedings of this workshop. http://www-f1.ijs.si/Bled2000.
8. Scattering Analysis Interactive Dial-up (SAID), Virginia Polytechnic Institute, Blacksburg, Virginia R. A. Arndt: Private Communication.
9. V. Hepp and H. Schleich, Z. Phys., **214** (1968), 71.
10. D. Stephen, Ph.D. thesis, Univ. of Massachusetts, 1970 (unpublished)
11. J. Dabrowski: Phys. Rev. **C60** (1999), 025205.