Short-range *NN* and *YN* interactions in the SU_6 quark model

C. Nakamoto (Suzuka College of Technology)
Y. Fujiwara (Kyoto University)
Y. Suzuki (Niigata University)
M. Kohno (Kyushu Dental College)

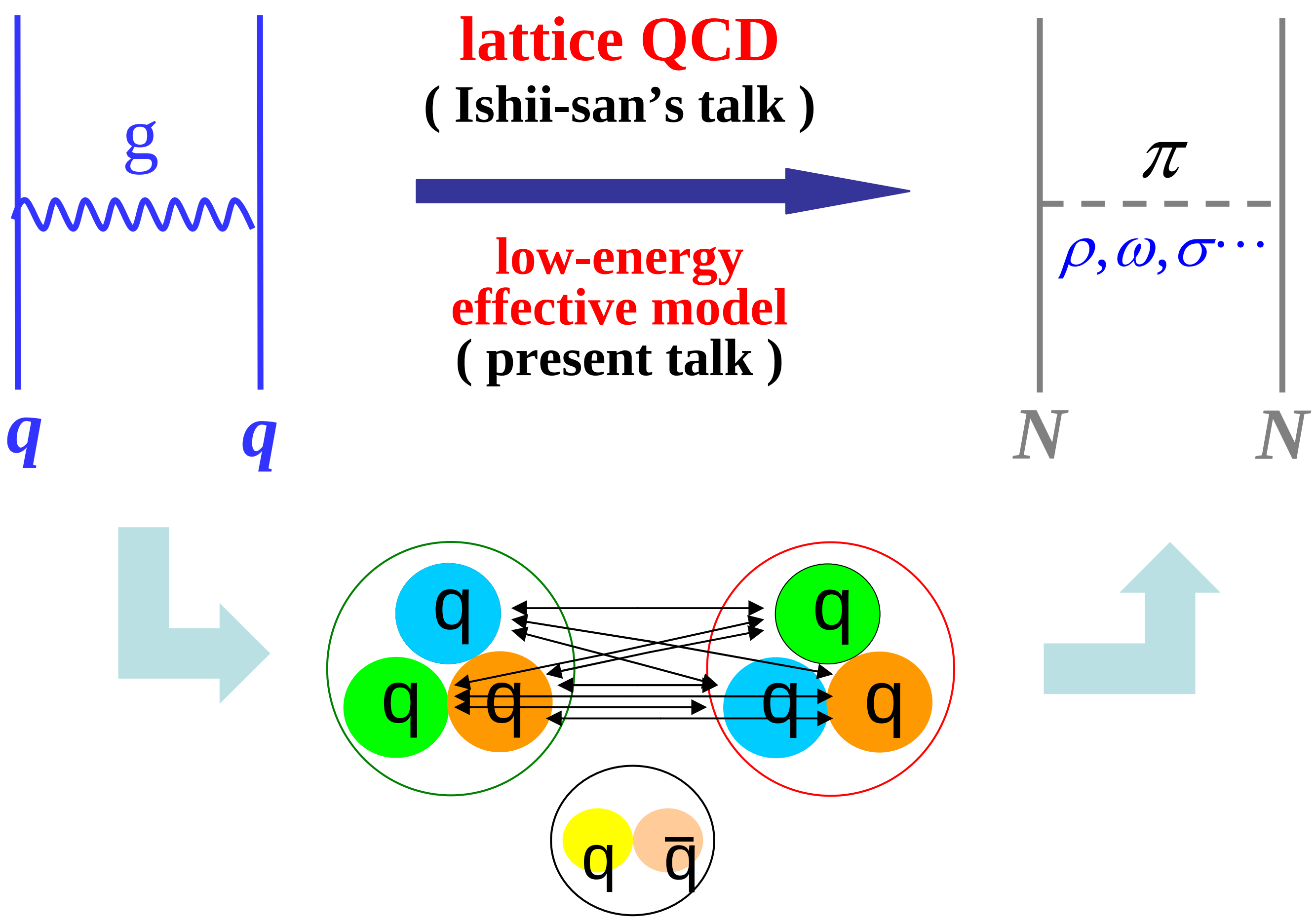
1. Introduction
2. Characteristic feature of a quark model
3. Realistic $B_8 B_8$ interaction in the SU_6 quark model
4. Results and discussion
5. Summary

Y. Fujiwara, Y. Suzuki and C. N., PPNP58 (2007) 439-520.

1. Introduction

From QCD to nuclear force

QCD **NN force**



Quarks and Baryons

u	d	s	c	b	t
up quark	down quark	strange quark	charm quark	bottom quark	top quark
～300 MeV	～300 MeV	～500 MeV	～1.3 GeV	～4.3 GeV	～186 GeV

(u, d, s) → These three quarks are regarded as the identical particles with the different quantum numbers ⇒ Flavor-*SU*(3) symmetry

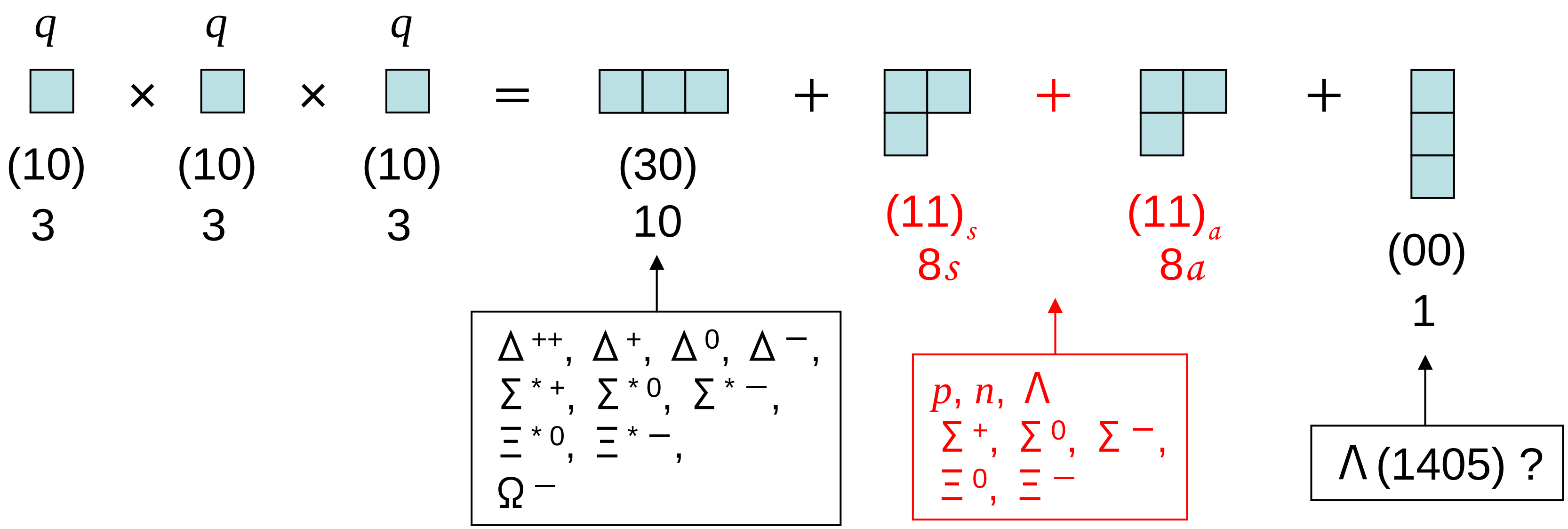
Octet baryons (with the spin value ½) : B_8

p	n	Λ	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
uud	udd	uds	uus	uds	dds	uss	dss
proton	**neutron**						

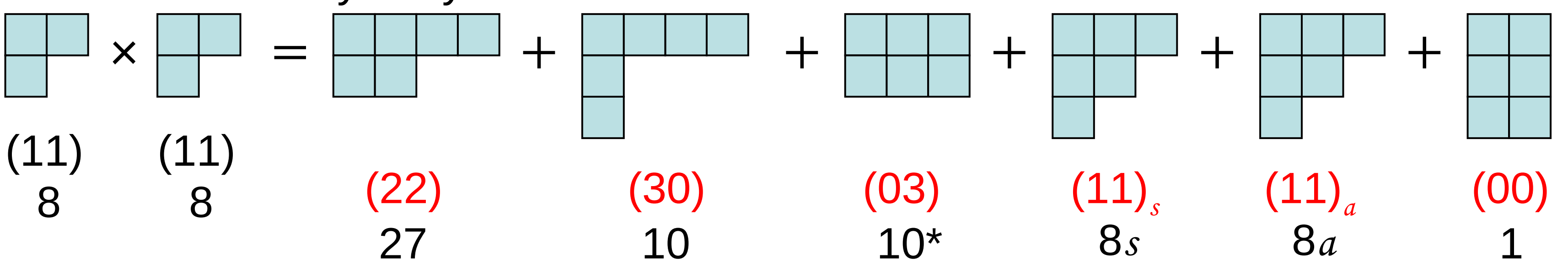
Nucleon (N): proton, neutron

Hyperon (Y): Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-

Classification by the flavor-SU(3) symmetry



For two octet-baryon system



If we assume that the flavor-SU(3) symmetry is satisfied completely,
the information of all $B_8 B_8$ systems are included in these 6-components !

$B_8 B_8$ systems

isospin basis	particle basis
• $NN(0)$, $NN(1)$	• pp, np, nn
□ $\Lambda N(1/2)$	□ Λp, Λn
□ $\Sigma N(1/2)$, $\Sigma N(3/2)$	□ $\Sigma^+ p$, $\Sigma^+ n$, $\Sigma^0 p$, $\Sigma^0 n$, $\Sigma^- p$, $\Sigma^- n$
□ $\Lambda\Lambda(0)$	□ $\Lambda\Lambda$
□ $\Xi N(0)$, $\Xi N(1)$	□ $\Xi^0 p$, $\Xi^0 n$, $\Xi^- p$, $\Xi^- n$
□ $\Sigma\Lambda(1)$	□ $\Sigma^+\Lambda$, $\Sigma^0\Lambda$, $\Sigma^-\Lambda$
□ $\Sigma\Sigma(0)$, $\Sigma\Sigma(1)$, $\Sigma\Sigma(2)$	□ $\Sigma^+\Sigma^+$, $\Sigma^+\Sigma^0$, $\Sigma^+\Sigma^-$, $\Sigma^0\Sigma^0$, $\Sigma^0\Sigma^-$, $\Sigma^-\Sigma^-$
□ $\Xi\Lambda(1/2)$	□ $\Xi^0\Lambda$, $\Xi^-\Lambda$
□ $\Xi\Sigma(1/2)$, $\Xi\Sigma(3/2)$	□ $\Xi^0\Sigma^+$, $\Xi^0\Sigma^0$, $\Xi^0\Sigma^-$, $\Xi^-\Sigma^+$, $\Xi^-\Sigma^0$, $\Xi^-\Sigma^-$
□ $\Xi\Xi(0)$, $\Xi\Xi(1)$	□ $\Xi^0\Xi^0$, $\Xi^0\Xi^-$, $\Xi^-\Xi^-$

SU(2) : Coupling of two spin-states

$$\phi_{S_1 S_{1z}} \phi_{S_2 S_{2z}} = \sum_{S S_z} \langle S_1 S_{1z} S_2 S_{2z} | S S_z \rangle [\phi_{S_1} \phi_{S_2}]_{S S_z}$$

Clebsch-Gordan coefficient

SU(3) : Coupling of two flavor-states

$$[B_1 B_2]^{\mathcal{P}}_{I I_z} = \frac{1}{\sqrt{2(1+\delta_{B_1 B_2})}} \left\{ [B_1 B_2]_{I I_z} + \mathcal{P}(-1)^{I_1+I_2-I} [B_2 B_1]_{I I_z} \right\}$$

$$= \sqrt{\frac{2}{1+\delta_{B_1 B_2}}} \sum_{(\lambda\mu)\rho \in \mathcal{P}} \langle (11)a_1 (11)a_2 \parallel (\lambda\mu)a; \rho \rangle \left[B_{(11)} B_{(11)} \right]_{(\lambda\mu)a;\rho}$$

Wigner coefficient

e.g.

$$[\Lambda N]^{\mathcal{P}=+1}_{\frac{1}{2} I_z} = \sqrt{2} \langle (11)00(11) - 3\tfrac{1}{2} \parallel (22) - 3\tfrac{1}{2} \rangle \left[B_{(11)} B_{(11)} \right]_{(22)-3\frac{1}{2} I_z} + \sqrt{2} \langle (11)00(11) - 3\tfrac{1}{2} \parallel (11) - 3\tfrac{1}{2} \rangle_{\rho=2} \left[B_{(11)} B_{(11)} \right]_{(11)-3\frac{1}{2} I_z}$$

$$= \frac{1}{\sqrt{10}} \left[B_{(11)} B_{(11)} \right]_{(22)-3\frac{1}{2} I_z} + \frac{3}{\sqrt{10}} \left[B_{(11)} B_{(11)} \right]_{(11)-3\frac{1}{2} I_z}$$

$B_8 B_8$ systems classified in the SU_3 states with (λ, μ)

S	$B_8B_8(I)$	^1E, ^3O (P=symmetric)	^3E, ^1O (P=unsymmetric)
0	NN(0)	—	(03)
	NN(1)	(22)	—
-1	ΛN	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(03)]$
	ΣN(1/2)	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(03)]$
	ΣN(3/2)	(22)	(30)
-2	ΛΛ	$\frac{1}{\sqrt{5}}(11)_s+\frac{9}{2\sqrt{30}}(22)+\frac{1}{2\sqrt{2}}(00)$	—
	ΞN(0)	$\frac{1}{\sqrt{5}}(11)_s-\sqrt{\frac{3}{10}}(22)+\frac{1}{\sqrt{2}}(00)$	$(11)_a$
	ΞN(1)	$\sqrt{\frac{3}{5}}(11)_s+\sqrt{\frac{2}{5}}(22)$	$\frac{1}{\sqrt{3}}[-(11)_a+(30)+(03)]$
	ΣΛ	$-\sqrt{\frac{2}{5}}(11)_s+\sqrt{\frac{3}{5}}(22)$	$\frac{1}{\sqrt{2}}[(30)-(03)]$
	ΣΣ(0)	$\sqrt{\frac{3}{5}}(11)_s-\frac{1}{2\sqrt{10}}(22)-\sqrt{\frac{3}{8}}(00)$	—
	ΣΣ(1)	—	$\frac{1}{\sqrt{6}}[2(11)_a+(30)+(03)]$
	ΣΣ(2)	(22)	—
-3	ΞΛ	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(30)]$
	ΞΣ(1/2)	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(30)]$
	ΞΣ(3/2)	(22)	(03)
-4	ΞΞ(0)	—	(30)
	ΞΞ(1)	(22)	—

Advantage of the SU_6 quark model

·If the Hamiltonian for the baryon-baryon interaction is approximately SU(3)-singlet, the B_8B_8 interactions with the same flavor-symmetry $(\lambda\mu)$ show the almost identical behavior for the states with the common spin-value.

↓

We may expect to understand the *YN* and *YY* interactions from the realistic *NN* interaction !

I will talk as follows,

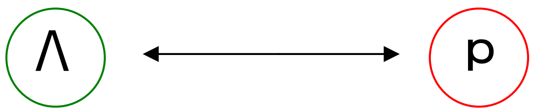
- General characteristic feature of a quark model
- Description of the realistic *NN* interaction in the SU_6 quark model (fss2 and FSS)

  ⇒ B_8B_8 interactions in the present model

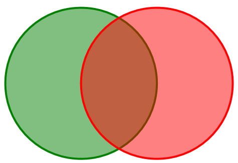
2. Characteristic feature of a quark model

Quark Pauli effect

Baryon level



heterogeneous particles

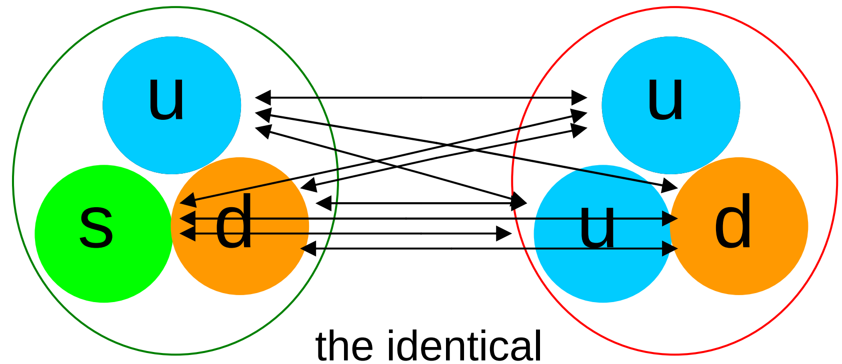


What will happen
if they overlap each other ?

We can see the quark-Pauli effect by introducing only the kinetic energy without any *qq* interaction

S. Saito, PTP40 (1968) 893; 41(1969) 705

Quark level



Λ

the identical particles with the different quantum numbers

p

Λp system consists of quark, which is the Fermi particle

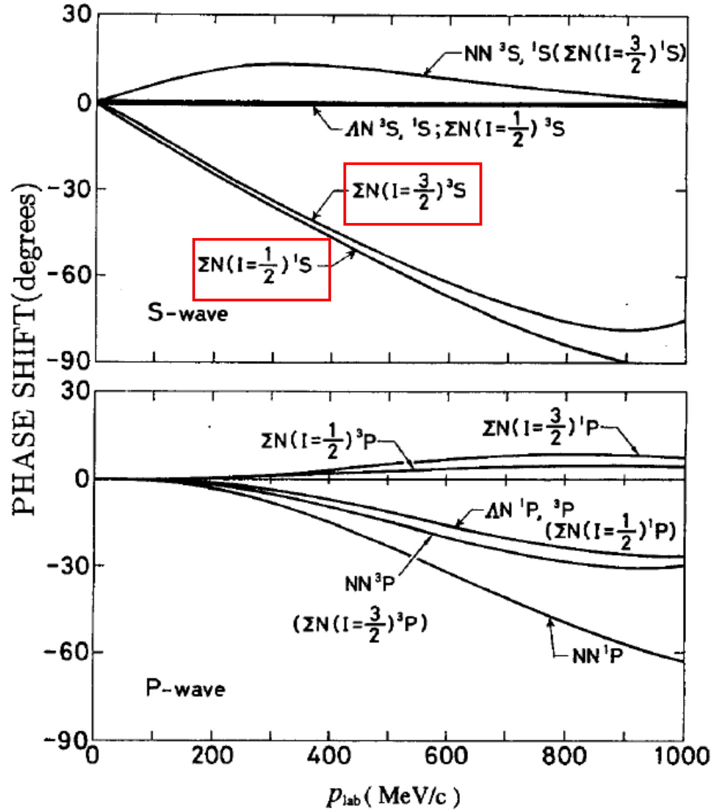
⇒ Antisymmetrization

state	$\mathcal{P}=+1$			$\mathcal{P}=-1$		
	(22)	$(11)_s$	(00)	(03)	$(11)_a$	(30)
eigen value	10/9	0	2	10/9	8/9	2/9
		↑ complete forbidden				↑ almost forbidden

Normalization kernel in the single-channel systems with $(0s)^6$ configuration $\langle\, \xi^{SFC} \,|\, \mathcal{A} \,|\, \xi^{SFC} \,\rangle$

S	B_8B_8	$^1S(\mathcal{P}=+1)$	$^3S(\mathcal{P}=-1)$
0	NN(I=0)		10/9
	NN(I=1)	10/9	
−1	ΛN	1	1
	ΣN(I=1/2)	1/9	1
	ΣN(I=3/2)	10/9	2/9
−2	ΛΛ	1	
	ΞN(I=0)	4/3	8/9
	ΞN(I=1)	4/9	20/27
	ΣΛ	2/3	2/3
	ΣΣ(I=0)	7/9	
	ΣΣ(I=1)		22/27
	ΣΣ(I=2)	10/9	
−3	ΞΛ	1	5/9
	ΞΣ(I=1/2)	1/9	5/9
	ΞΣ(I=3/2)	10/9	10/9
−4	ΞΞ(I=0)		2/9
	ΞΞ(I=1)	10/9	

phase shifts given by solving the RGM equation only with the kinetic energy term, namely, no *qq* interaction



Indication of the quark-Pauli effect in the hypernuclear physics

$$\left|\Sigma N\left(I=\frac{1}{2}\right)\,{}^1S_0\right\rangle = \frac{1}{\sqrt{10}}\left[3\,(11)_s - (22)\right]$$

$$\left|\Sigma N\left(I=\frac{3}{2}\right)\,{}^3S_1\right\rangle = (30)$$

$(11)_s$: Pauli forbidden state → ΣN(1/2) ${}^1S_0$-state (90%)

(30) : almost Pauli forbidden state → ΣN(3/2) ${}^3S_1$-state

} Repulsive ?

Oka *et al*., NPA464(1987)700

↓

It generates the repulsive Σ single-particle potential !

$\Rightarrow$ It agrees with the experimental data about (π^-,K^+) inclusive spectra on ^{28}Si

Noumi *et al*. PRL89 (2002) 072301; 90 (2003) 049902 (E)

Any realistic *BB* interaction in the meson-exchange model generate the attractive Σ single-particle potential

others

$$\left|\Xi\Sigma\left(I=\frac{1}{2}\right)\,{}^1S_0\right\rangle = \frac{1}{\sqrt{10}}\left[3\,(11)_s - (22)\right]$$

$$\left|\Xi\Xi\,(I=0)\,{}^3S_1\right\rangle = (30)$$

Color analogue of Fermi-Breit (FB) interaction

Rujula *et al*. PRD12(1975)147

- the color analogue of FB interaction represents the one-gluon exchange potential (OGEP)
- All the contributions from the FB interaction are generated from the quark-exchange diagrams, since we assume color-singlet cluster wave-functions as the (3q)-(3q) system.

⇩ M. Oka and K. Yazaki, PL90B (1980) 41, PTP66 (1981) 556, 572

All contributions from the FB interaction are short-range interaction !

Short-range central repulsion

color-magnetic interaction

$$U_{ij}^{\mathrm{CM}} = -\frac{1}{4}\alpha_S(\lambda_i \cdot \lambda_j) \cdot \frac{\pi}{2}\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4}{3m_i m_j}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\right)\delta(\boldsymbol{r}_{ij})$$

derives from the color analogue of FB interaction that represents the OGEP.

⇒ It generates the short-range repulsion in all flavor-*SU*(3) states except for the flavor-singlet (00) state

H - particle state

R. L. Jaffe, PRL38 (1977) 195, 617E

It may be interpreted qualitatively as the origin of well-known repulsive feature of the nuclear force at the high-energy region.

Large anti-symmetric *LS* force

spin-orbit (*LS*) term

$$-\frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{1}{8}\cdot\frac{1}{r_{ij}^3}\left[\boldsymbol{r}_{ij}\times(\boldsymbol{p}_i-\boldsymbol{p}_j)\right]\cdot\left\{\frac{1}{m_i^2}\boldsymbol{\sigma}_i+\frac{1}{m_j^2}\boldsymbol{\sigma}_j+\frac{2}{m_im_j}(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\right\}$$

derives from the color analogue of FB interaction that represents the OGEP.

The *YN* interaction induces the channel coupling with spin-flip, for example, ${}^1P_1$-${}^3P_1$ coupling, which is forbidden in the *NN* system.
⇒ due to $LS^{(-)}$ force (anti-symmetric spin-orbit force)

The opposite contribution between *LS* and $LS^{(-)}$ in the Λ-hypernuclei ⟷ In the experiment, very small spin-orbit splitting in the energy spectra of ${}^{9}_{\Lambda}$Be and ${}^{13}_{\Lambda}$C

Morimatsu *et al*., NPA420(1984)573

H. Akikawa *et al*., PRL88 (2002) 082501
H. Tamura *et al*., NPA754 (2005) 58c

Consistent !

Large $LS^{(-)}$ contribution from the FB interaction

(Relatively small $LS^{(-)}$ contribution from the meson-exchange model)

Quark model with FB interaction

- Advantage

(1) Quark Pauli effect

(2) Short-range central repulsion

(3) Large anti-symmetric *LS* force

[Short-range tensor force derived from FB interaction is weak.]

- Defect

(1) Missing of the medium-range attraction

(2) Missing of the long-range spin-dependent force

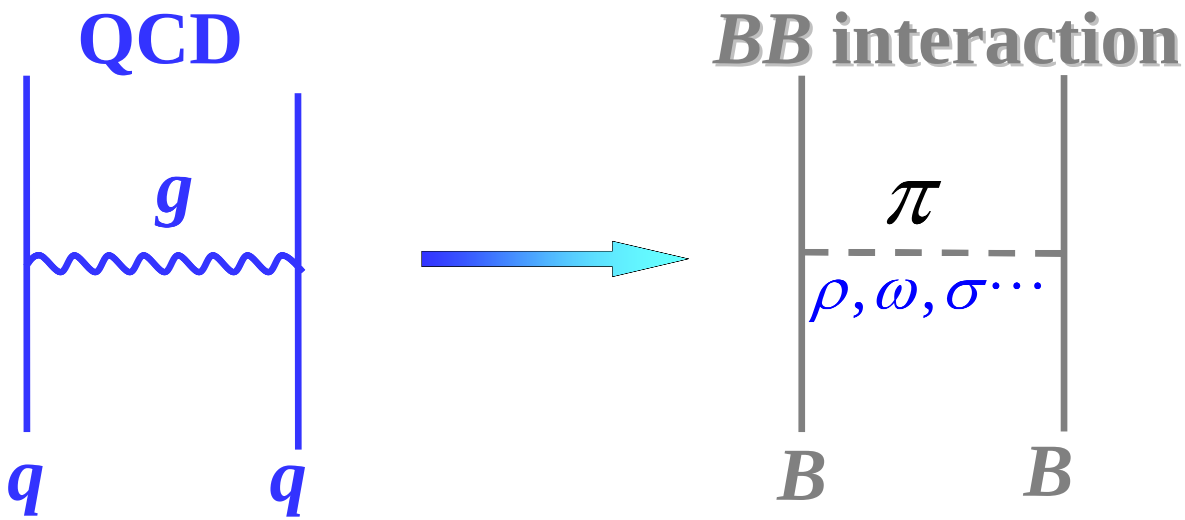
↓ **Reason : no meson effect**

Introduction of the effective meson exchange potential (EMEP) between quarks

3. Realistic $B_8 B_8$ interaction in the SU_6 quark model

(fss2, so-called Kyoto-Niigata model)

From *qq* interaction to *BB* interaction



QCD characteristics

1. color degrees

g：color octet

***q*: color triplet**

2. confinement

3. asymptotic freedom

4. meson exchange effect

Simplification

g exchange effect →*qq* potential

antisymmetrization among quarks

phenomenological r^2 potential

OGEP → color analogue of Fermi-Breit interaction

EMEP acting between quarks

B_8B_8 interactions by fss2 PPNP58 (2007) 439-520

A natural and accurate description of *NN*, *YN*, *YY* interactions in terms of (3*q*)-(3*q*) RGM

- **Short-range repulsion and *LS* by quarks**
- **Medium-attraction and long-rang tensor by S, PS and V meson exchange potentials (fss2) (*Cf*. FSS without V : PRC54 (1996) 2180)**

quark Hamiltonian

$$H = \sum_{i=1}^{6} (m_i + p_i^2/2m_i)$$

$$+ \sum_{i<j}^{6} \left(U_{ij}^{\mathrm{Conf}} + U_{ij}^{\mathrm{FB}} + \sum_\beta U_{ij}^{\mathrm{S}\beta} + \sum_\beta U_{ij}^{\mathrm{PS}\beta} + \sum_\beta U_{ij}^{\mathrm{V}\beta}\right)$$

- $U_{ij}^{\mathrm{Conf}} \propto r_{ij}^2$
- U_{ij}^{FB} : Fermi-Breit interaction
- $U_{ij}^{\mathrm{S}\beta}$: scalar-meson exchange
- $U_{ij}^{\mathrm{PS}\beta}$: pseudo-scalar-meson exchange
- $U_{ij}^{\mathrm{V}\beta}$: vector-meson exchange

color analogue of Fermi- Breit interaction (in momentum space)

$$U_{ij}^{\rm FB} = U_{ij}^{\rm C} + U_{ij}^{\rm MR} + U_{ij}^{\rm CM} + U_{ij}^{\rm sLS} + U_{ij}^{\rm aLS} + U_{ij}^{\rm GT}$$

with

$$\begin{aligned}
U_{ij}^{\rm C} &= \frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{4\pi}{\boldsymbol{k}^2} \\
U_{ij}^{\rm MR} &= \frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{4\pi}{\boldsymbol{k}^2}\cdot\frac{1}{m_im_j}\left[\frac{1}{\boldsymbol{k}^2}(\boldsymbol{k}\cdot\boldsymbol{p}_i)(\boldsymbol{k}\cdot\boldsymbol{p}_j)-(\boldsymbol{p}_i\cdot\boldsymbol{p}_j)\right] \\
U_{ij}^{\rm CM} &= -\frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{\pi}{2}\left(\frac{1}{m_i^2}+\frac{1}{m_j^2}+\frac{4}{3m_im_j}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\right) \\
U_{ij}^{\rm sLS} &= \frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{1}{4}\cdot\frac{4\pi}{\boldsymbol{k}^2}i\ \left[\boldsymbol{k},\ \frac{\boldsymbol{p}_i-\boldsymbol{p}_j}{2}\right]\cdot\left\{\frac{1}{m_i^2}\boldsymbol{\sigma}_i+\frac{1}{m_j^2}\boldsymbol{\sigma}_j+\frac{2}{m_im_j}(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\right\} \\
U_{ij}^{\rm aLS} &= \frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{1}{8}\cdot\frac{4\pi}{\boldsymbol{k}^2}i\ \left[\boldsymbol{k},\ \boldsymbol{p}_i+\boldsymbol{p}_j\right]\cdot\left\{\frac{1}{m_i^2}\boldsymbol{\sigma}_i-\frac{1}{m_j^2}\boldsymbol{\sigma}_j-\frac{2}{m_im_j}(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\right\} \\
U_{ij}^{\rm GT} &= \frac{1}{4}\alpha_S(\lambda_i\cdot\lambda_j)\cdot\frac{1}{4}\cdot\frac{4\pi}{\boldsymbol{k}^2}\cdot\frac{1}{m_im_j}\left\{(\boldsymbol{\sigma}_i\cdot\boldsymbol{k})(\boldsymbol{\sigma}_j\cdot\boldsymbol{k})-\frac{(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}^2}{3}\right\}
\end{aligned}$$

where $\boldsymbol{k}=\boldsymbol{q}_f-\boldsymbol{q}_i$

meson-exchange *qq* potentials

$$U^{\rm S}(\boldsymbol{q}_f,\boldsymbol{q}_i) = gg^\dagger \frac{4\pi}{\boldsymbol{k}^2+m^2}\left\{ -1 + \frac{\boldsymbol{q}^2}{2m_{ud}^2} - \frac{1}{2m_{ud}^2} i\boldsymbol{n}\cdot\boldsymbol{S}\right\}$$

$$U^{\rm PS}(\boldsymbol{q}_f,\boldsymbol{q}_i) = -ff^\dagger \frac{1}{m_{\pi^+}^2}\frac{4\pi}{\boldsymbol{k}^2+m^2}\left[(\boldsymbol{\sigma}_1\cdot\boldsymbol{k})(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}) - (1-c_\delta)(m^2+\boldsymbol{k}^2)\frac{1}{3}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\right]$$

$$U^{\rm V}(\boldsymbol{q}_f,\boldsymbol{q}_i) = \frac{4\pi}{\boldsymbol{k}^2+m^2}\left\{ f^e f^{e\dagger}\left(1+\frac{3\boldsymbol{q}^2}{2m_{ud}^2}\right) - f^m f^{m\dagger}\frac{2}{(m_{ud}m)^2}\left[(\boldsymbol{\sigma}_1\cdot\boldsymbol{n})(\boldsymbol{\sigma}_2\cdot\boldsymbol{n}) - (1-c_{qss})\frac{1}{3}\boldsymbol{n}^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\right]\right.$$
$$\left. - \left(f^m f^{e\dagger} + f^e f^{m\dagger}\right)\frac{2}{m_{ud}m} i\boldsymbol{n}\cdot\boldsymbol{S}\right\}$$

where

$\boldsymbol{k} = \boldsymbol{q}_f - \boldsymbol{q}_i,\ \boldsymbol{q} = (\boldsymbol{q}_f + \boldsymbol{q}_i)/2$

and $\boldsymbol{n} = [\boldsymbol{q}\times\boldsymbol{k}]$.

$$gf^\dagger \longrightarrow \left\{ \begin{array}{c} g_1 f_1 \\ g_8 f_8 \Sigma'_\beta \lambda_\beta(i)\lambda_\beta(j) \end{array}\right.$$

with singlet-octet meson mixing

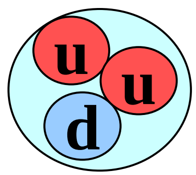
Resonating-Group Method

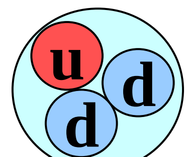
equations

a method developed in the cluster models of light nuclei

Antisymmetrized (RGM) wave function

ϕ : [$(0s)^3 \times$ spin $\times$ flavor] wave functions

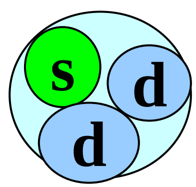
$\Psi =$ ϕ 

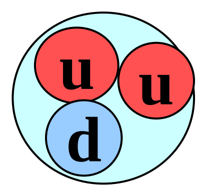
ϕ 

$\chi(r)$

p *n*

or

$\Psi =$ ϕ 

ϕ 

$\chi(r)$

Σ^- *p*

relative wave function

Lippmann-Schwinger (LS) RGM

PTP 103 (2000) 755

RGM Equation

$$\langle \phi(3q)\phi(3q)|E-H|\mathcal{A}\{\phi(3q)\phi(3q)\chi(\boldsymbol{r})\}\rangle=0$$

- **Solve $[\varepsilon-H_0-V_{\mathrm{RGM}}(\varepsilon)]\chi=0$ in the momentum representation, where $V_{\mathrm{RGM}}(\varepsilon)=V_{\mathrm{D}}+G+\varepsilon K$**
- **Born amplitudes $\langle q_{\mathrm{f}}|V_{\mathrm{RGM}}(\varepsilon)|q_{\mathrm{i}}\rangle$** PTP 104 (2000) 1025

$V_{\mathrm{RGM}}(\varepsilon)$ is non-local, energy dependent and sometimes involves the Pauli forbidden state.

EMEP direct terms

$$M_D^S(\boldsymbol{q}_f,\boldsymbol{q}_i) = g^2 \frac{4\pi}{\boldsymbol{k}^2+m^2} e^{-\frac{1}{3}(bk)^2} \left\{ X^C_{0D_+} \left[-1 + \frac{1}{2(3m_{ud})^2}\left(\boldsymbol{q}^2 + \frac{9}{2b^2}\right) \right] - \frac{3}{2(3m_{ud})^2} X^{LS}_{0D_+} i\boldsymbol{n}\cdot\boldsymbol{S} - \frac{3}{2(3m_{ud})^2} X^{LS(-)}_{0D_+} i\boldsymbol{n}\cdot\boldsymbol{S}^{(-)} \right\}$$

$$M_D^{PS}(\boldsymbol{q}_f,\boldsymbol{q}_i) = -f^2 \frac{1}{m^2_{\pi^+}} \frac{4\pi}{\boldsymbol{k}^2+m^2} e^{-\frac{1}{3}(bk)^2} X^T_{0D_+} \left[(\boldsymbol{\sigma}_1\cdot\boldsymbol{k})(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}) - (1-c_\delta)\frac{(m^2+\boldsymbol{k}^2)}{3}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) \right]$$

$$M_D^V(\boldsymbol{q}_f,\boldsymbol{q}_i) = \frac{4\pi}{\boldsymbol{k}^2+m^2} e^{-\frac{1}{3}(bk)^2} \left\{ (f^e)^2\, X^C_{0D_+} \left[1 + \frac{3}{2(3m_{ud})^2}\left(\boldsymbol{q}^2+\frac{9}{2b^2}\right) \right] - (f^m)^2 \frac{2}{(3m_{ud}m)^2} X^T_{0D_+} \left[(\boldsymbol{\sigma}_1\cdot\boldsymbol{n})(\boldsymbol{\sigma}_2\cdot\boldsymbol{n}) - (1-c_{qss})\left(\frac{\boldsymbol{n}^2}{3}+\frac{\boldsymbol{k}^2}{b^2}\right)(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) + \frac{3}{2b^2}[\boldsymbol{\sigma}_1\times\boldsymbol{k}]\cdot[\boldsymbol{\sigma}_2\times\boldsymbol{k}] \right] - 2f^m f^e \frac{2}{3m_{ud}m} X^{LS}_{0D_+} i\boldsymbol{n}\cdot\boldsymbol{S} - 2f^m f^e \frac{2}{3m_{ud}m} X^{LS(-)}_{0D_+} i\boldsymbol{n}\cdot\boldsymbol{S}^{(-)} \right\}$$

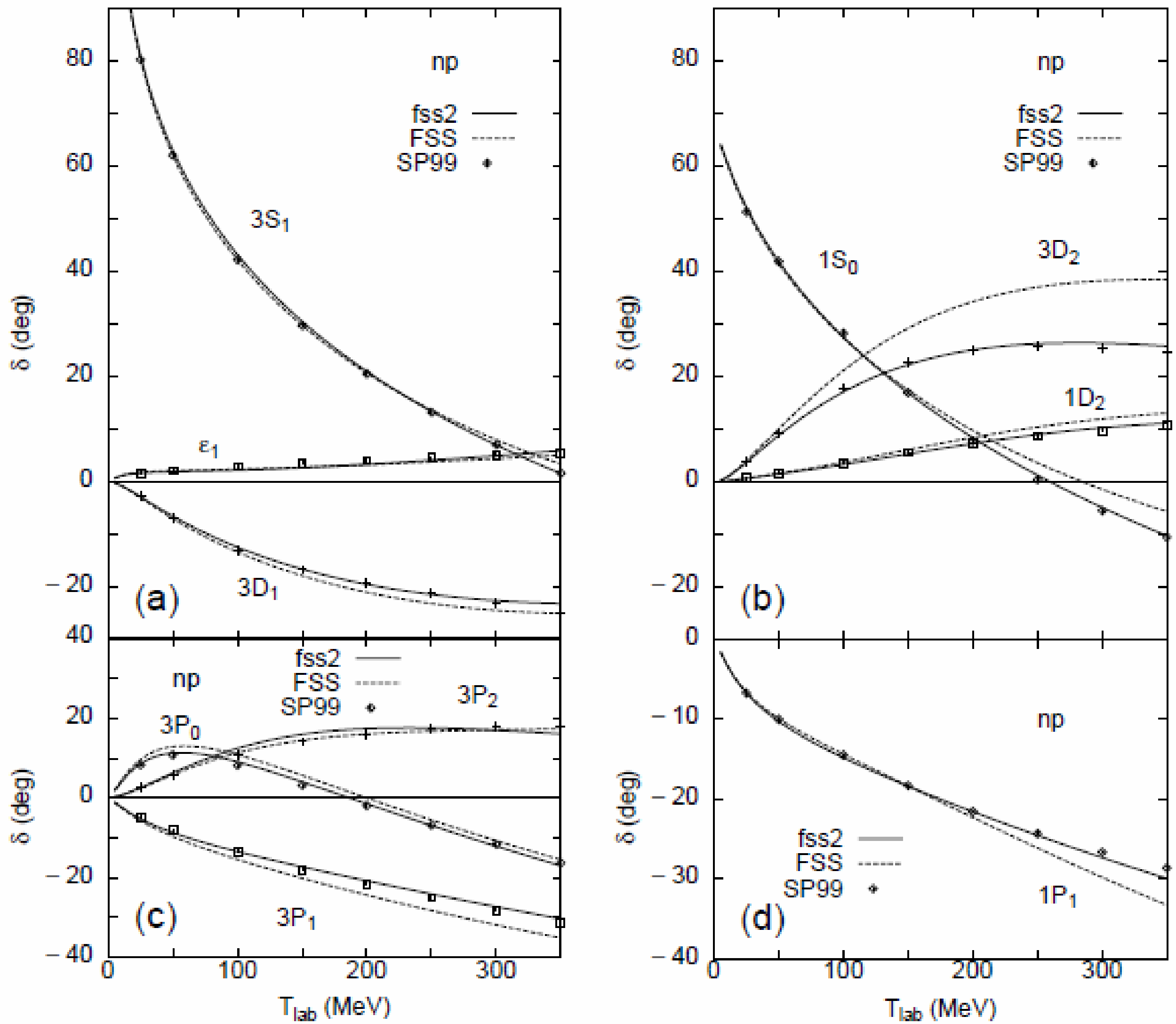
where $X^{\Omega}_{x\mathcal{T}}$ are spin-flavor (-color) factors.

model parameters

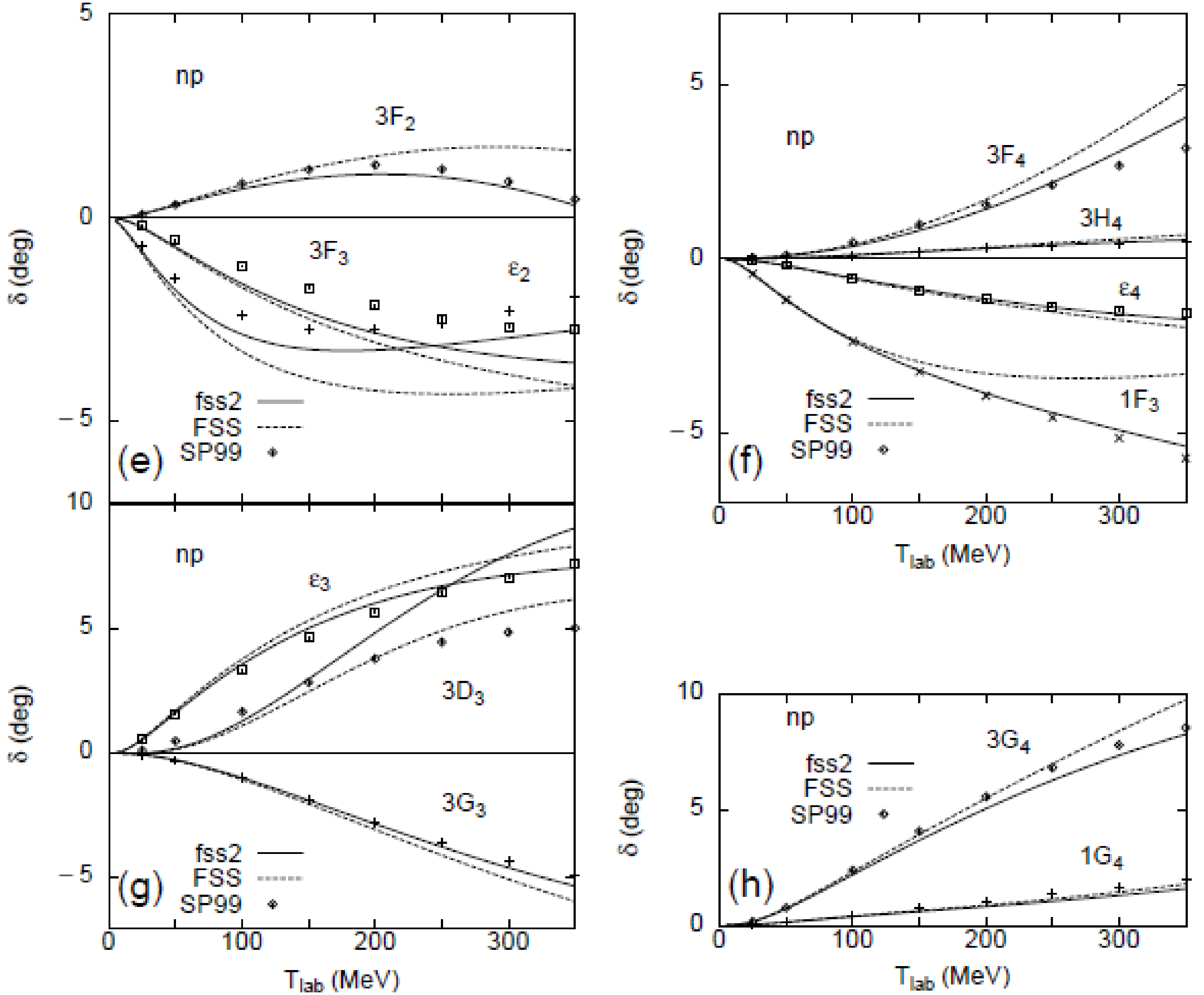
	b (fm)	m_{ud} (MeV/c^2)	α_S	$\lambda = m_s/m_{ud}$
FSS	0.616	360	2.1742	1.526
fss2	0.5562	400	1.9759	1.5512
	f_1^S	f_8^S	θ^S	θ_4^S 1)
FSS	2.89138	1.07509	27.78°	65°
fss2	3.48002	0.94459	33.3295°	55.826°
	f_1^{PS}	f_8^{PS}	θ^{PS}	
FSS	0.21426	0.26994	−23°	
fss2	—	0.26748	—	(no η, η')
	f_1^{Ve}	f_8^{Ve}	f_1^{Vm}	f_8^{Vm} 2)
fss2	1.050	0	1.000	2.577
	m_ϵ	m_{S^*}	m_δ	m_κ (MeV/c^2)
FSS	800	1250	970	1145
fss2	800	1250	846 3)	936
	c_δ	c_{qss}	c_{qT}	
FSS	0.381	—	—	
fss2	0.4756 4)	0.6352	3.139 5)	

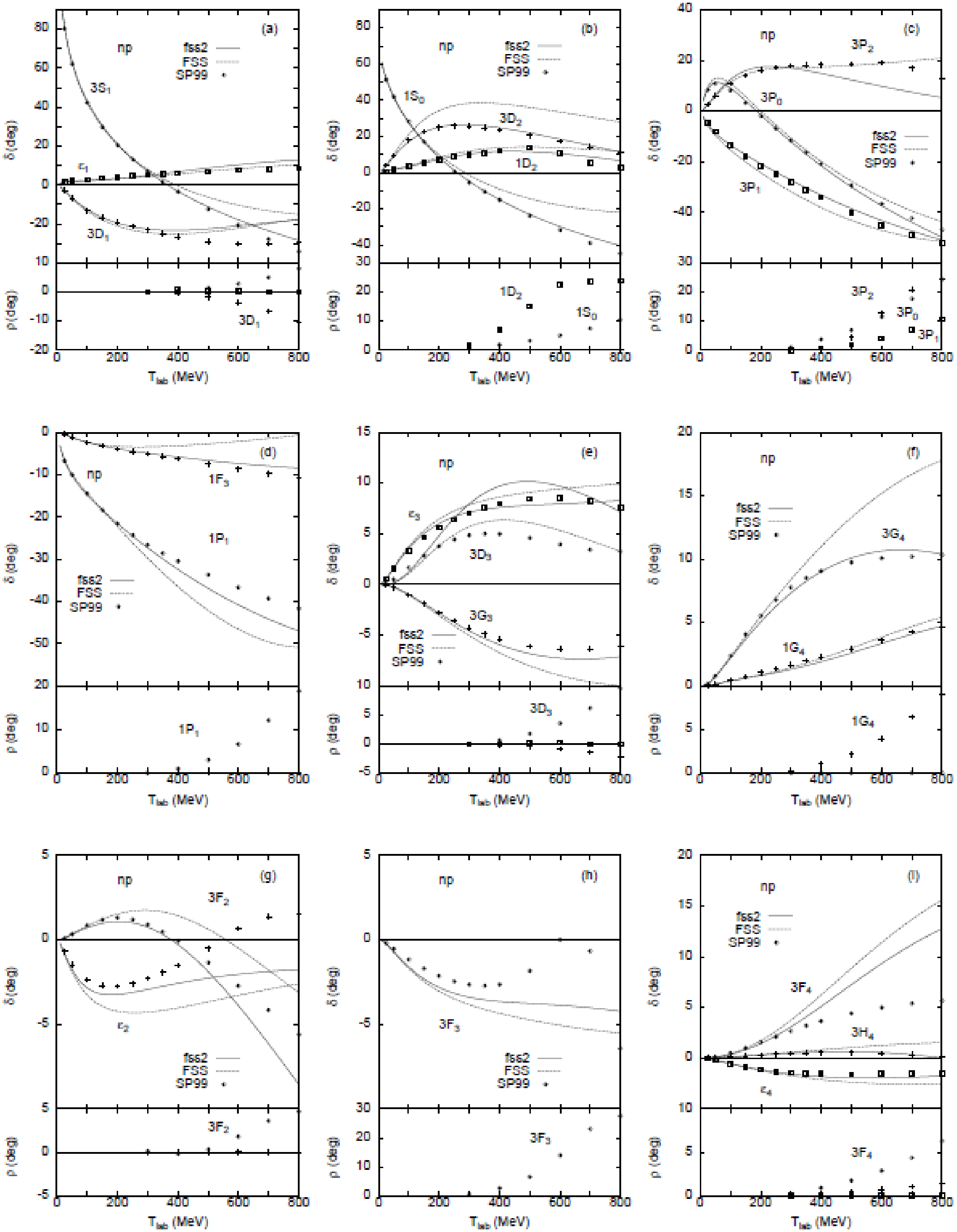
1) θ_4^S is used only for $\Sigma N(I = 3/2)$.
2) $\theta^V = 35.264°$ (ideal mixing), no vector tensor, two-pole ρ meson : 664.56 MeV (0.34687) and 917.772 MeV (0.48747) are used.
3) $m_\delta = 720$ MeV/c^2 is used only for NN.
4) only for π, otherwise 1.
5) augment the Fermi-Breit tensor term by c_{qT}.

np phase shifts by fss2 (J=0–2)

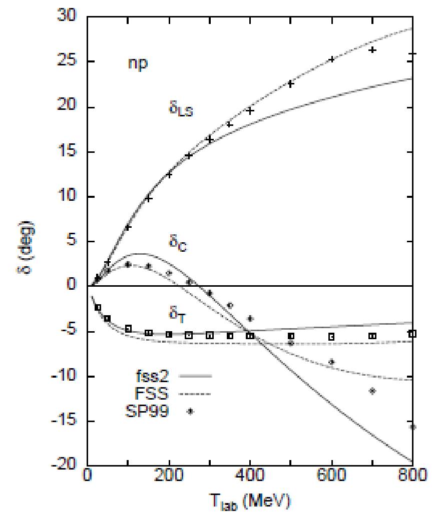


np phase shifts by fss2 (J=2−4)



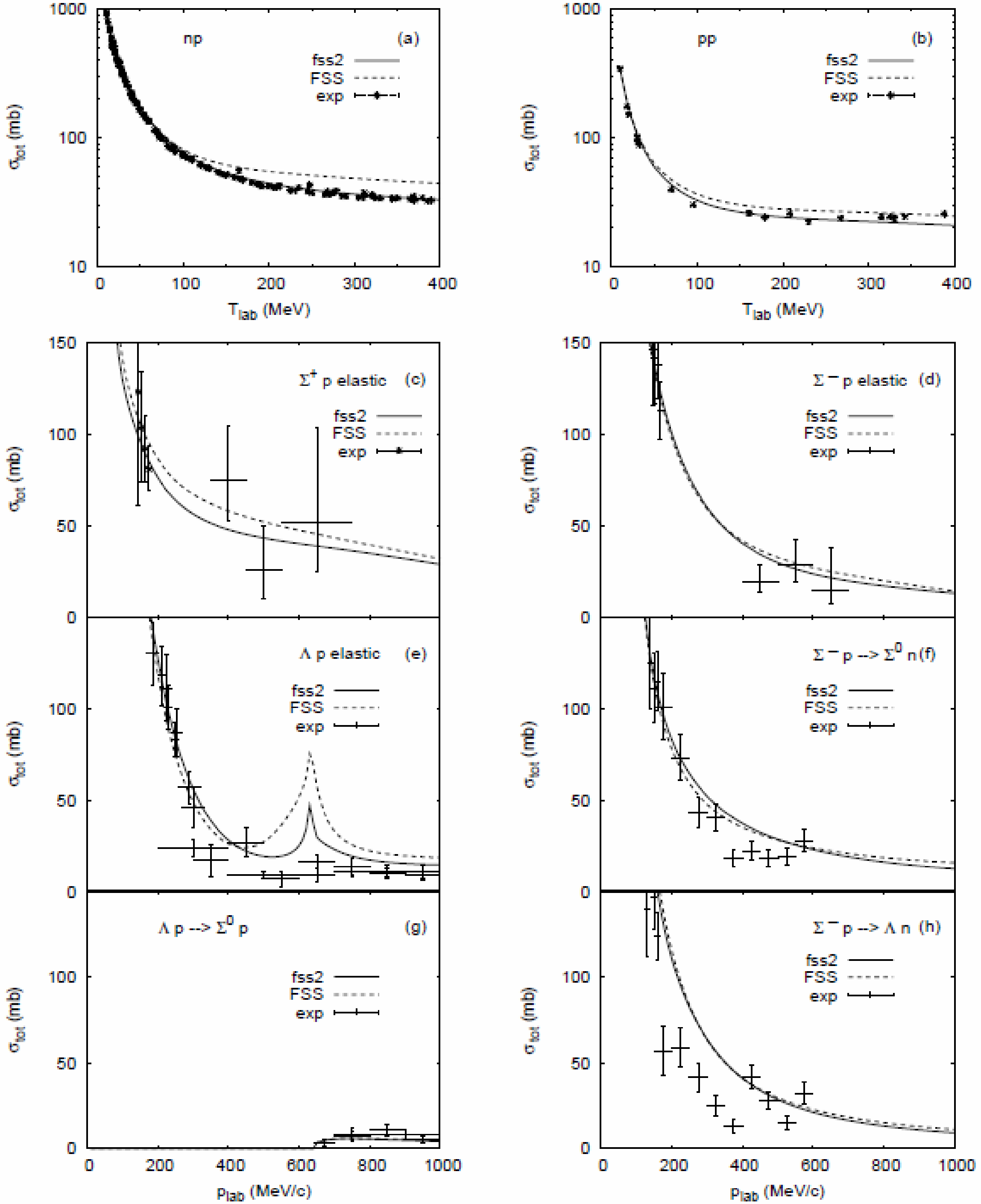


np phase shifts by fss2 and FSS for $T_{lab} < 800$ MeV. Some empirical inelasticity parameters ρ are also shown for $T_{lab} > 300$ MeV.



Decomposition of the ^3P_J phase shifts for the np scattering to the central(δ_C), *LS*(δ_{LS}), tensor(δ_T) components.

NN and *YN* total cross sections



Deuteron properties by fss2 in three different calculational schemes, compared with the predictions of the Bonn model-C potential and the experiment

	isospin basis	particle basis		Bonn C	Expt.
		Coulomb off	Coulomb on		
ϵ_d (MeV)	2.2250	2.2261	2.2309	fitted	2.224644 ± 0.000046
P_D (%)	5.490	5.490	5.494	5.60	
$\eta = A_D/A_S$	0.02527	0.02527	0.02531	0.0266	0.0256 ± 0.0004
rms (fm)	1.9598	1.9599	1.9582	1.968	1.9635 ± 0.0046
Q_d (fm^2)	0.2696	0.2696	0.2694	0.2814	0.2860 ± 0.0015
μ_d (μ_N)	0.8485	0.8485	0.8485	0.8479	0.85742

Effective range parameters of fss2 for the NN interactions

		isospin basis	particle basis		Expt.
			Coulomb off	Coulomb on	
$pp\ ^1S_0$	a		-17.80	$\underline{-7.810}$	-7.819 ± 0.0026
	r		2.680	2.581	2.794 ± 0.0014
	P		0.061	-0.064	
$pp\ ^3P_0$	a		-2.876	-3.117	$-4.82 \pm 1.11,\ -2.71 \pm 0.34$
	r		3.834	3.735	$7.14 \pm 0.93,\ 3.8 \pm 1.1$
	P		-0.011	-0.034	
$pp\ ^3P_1$	a		1.821	1.992	$1.78 \pm 0.10,\ 1.97 \pm 0.09$
	r		-8.162	-7.5666	$-7.85 \pm 0.52,\ -8.27 \pm 0.37$
	P		0.001	0.001	
$nn\ ^1S_0$	a		-18.04	-18.04	$-18.05 \pm 0.3,\ -18.9 \pm 0.4$
	r		2.677	2.677	2.75 ± 0.11
	P		0.061	0.061	
$nn\ ^3P_0$	a		-2.881	-2.881	
	r		3.825	3.825	
	P		-0.011	-0.011	
$nn\ ^3P_1$	a		1.823	1.823	
	r		-8.154	-8.155	
	P		0.001	0.001	
$np\ ^1S_0$	a	$\underline{-23.76}$	-27.39	-27.87	-23.748 ± 0.010
	r	2.588	2.532	2.529	2.75 ± 0.05
	P	0.059	0.052	0.052	
$np\ ^3P_0$	a	-2.740	-2.466	-2.466	
	r	3.869	3.930	3.930	
	P	-0.013	-0.018	-0.018	
$np\ ^3S_1$	a	5.399	5.400	5.395	5.424 ± 0.004
	r	1.735	1.735	1.734	1.759 ± 0.005
	P	0.063	0.063	0.063	
$np\ ^1P_1$	a	2.824	2.826	2.826	
	r	-6.294	-6.300	-6.300	
	P	-0.006	-0.006	-0.006	
$np\ ^3P_1$	a	1.740	1.582	1.582	
	r	-8.198	-8.185	-8.185	
	P	0.001	0.000	0.000	

4. Results and discussion

Flavor-SU(3) dependence of the B_8B_8 intereactions

If the Hamiltonian is approximately SU(3) scalar, we can expect that the baryon-baryon interactions with the same *SU*(3) representation should be very similar.

S	B_8B_8 (I)	$\mathcal{P}=+1$ (symmetric)	$\mathcal{P}=-1$ (antisymmetric)
		${}^1E$ or ${}^3O$	${}^3E$ or ${}^1O$
0	NN $(I=0)$	–	(03)
	NN $(I=1)$	(22)	–
−1	ΛN	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(03)]$
	ΣN $(I=1/2)$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(03)]$
	ΣN $(I=3/2)$	(22)	(30)
−2	$\Lambda\Lambda$	$\frac{1}{\sqrt{5}}(11)_s+\frac{9}{2\sqrt{30}}(22)+\frac{1}{2\sqrt{2}}(00)$	–
	ΞN $(I=0)$	$\frac{1}{\sqrt{5}}(11)_s-\sqrt{\frac{3}{10}}(22)+\frac{1}{\sqrt{2}}(00)$	$(11)_a$
	ΞN $(I=1)$	$\sqrt{\frac{3}{5}}(11)_s+\sqrt{\frac{2}{5}}(22)$	$\frac{1}{\sqrt{3}}[-(11)_a+(30)+(03)]$
	$\Sigma\Lambda$	$-\sqrt{\frac{2}{5}}(11)_s+\sqrt{\frac{3}{5}}(22)$	$\frac{1}{\sqrt{2}}[(30)-(03)]$
	$\Sigma\Sigma$ $(I=0)$	$\sqrt{\frac{3}{5}}(11)_s-\frac{1}{2\sqrt{10}}(22)-\sqrt{\frac{3}{8}}(00)$	–
	$\Sigma\Sigma$ $(I=1)$	–	$\frac{1}{\sqrt{6}}[2(11)_a+(30)+(03)]$
	$\Sigma\Sigma$ $(I=2)$	(22)	–
−3	$\Xi\Lambda$	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(30)]$
	$\Xi\Sigma$ $(I=1/2)$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(30)]$
	$\Xi\Sigma$ $(I=3/2)$	(22)	(03)
−4	$\Xi\Xi$ $(I=0)$	–	(30)
	$\Xi\Xi$ $(I=1)$	(22)	–

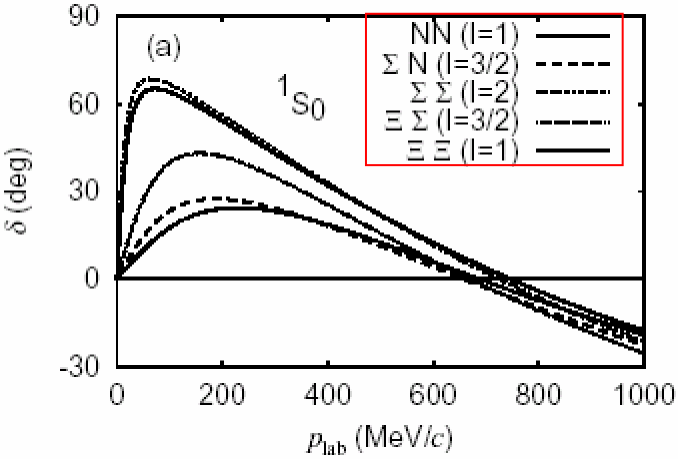
(22) NN(I=1)
ΣN(I=3/2) , ΣΣ(I=2)
ΞΣ(I=3/2), ΞΞ(I=1)

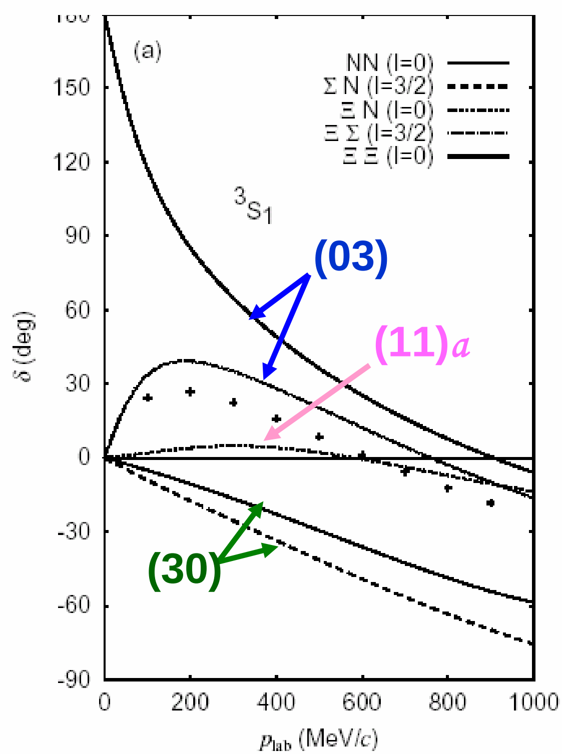
(03) : NN(I=0) ⟷ ΞΣ(I=3/2)

(30) : ΣN(I=3/2) ⟷ ΞΞ(I=0)

The feature of the NN(I=0) interaction succeeds to the ΞΣ(I=3/2) interaction !?

Flavor-SU(3) dependence of the B_8B_8 intereactions





S	$B_8B_8\ (I)$	$\mathcal{P}=+1$ (symmetric) ^1E or ^3O	$\mathcal{P}=-1$ (antisymmetric) ^3E or ^1O
0	$NN\ (I=0)$	–	(03)
	$NN\ (I=1)$	(22)	–
-1	ΛN	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(03)]$
	$\Sigma N\ (I=1/2)$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(03)]$
	$\Sigma N\ (I=3/2)$	(22)	(30)
-2	$\Lambda\Lambda$	$\frac{1}{\sqrt{5}}(11)_s+\frac{9}{2\sqrt{30}}(22)+\frac{1}{2\sqrt{2}}(00)$	–
	$\Xi N\ (I=0)$	$\frac{1}{\sqrt{5}}(11)_s-\sqrt{\frac{3}{10}}(22)+\frac{1}{\sqrt{2}}(00)$	$(11)_a$
	$\Xi N\ (I=1)$	$\sqrt{\frac{3}{5}}(11)_s+\sqrt{\frac{2}{5}}(22)$	$\frac{1}{\sqrt{3}}[-(11)_a+(30)+(03)]$
	$\Sigma\Lambda$	$-\sqrt{\frac{2}{5}}(11)_s+\sqrt{\frac{3}{5}}(22)$	$\frac{1}{\sqrt{2}}[(30)-(03)]$
	$\Sigma\Sigma\ (I=0)$	$\sqrt{\frac{3}{5}}(11)_s-\frac{1}{2\sqrt{10}}(22)-\sqrt{\frac{3}{8}}(00)$	–
	$\Sigma\Sigma\ (I=1)$	–	$\frac{1}{\sqrt{6}}[2(11)_a+(30)+(03)]$
	$\Sigma\Sigma\ (I=2)$	(22)	–
-3	$\Xi\Lambda$	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(30)]$
	$\Xi\Sigma\ (I=1/2)$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(30)]$
	$\Xi\Sigma\ (I=3/2)$	(22)	(03)
-4	$\Xi\Xi\ (I=0)$	–	(30)
	$\Xi\Xi\ (I=1)$	(22)	–

Behavior of the $B_8 B_8$ interaction in each flavor-$SU(3)$ symmetry in the SU_6 quark model

(22) : attractive with core

(00) : attractive without core

(03) : attractive with core

(30) : almost forbidden state

$(11)_s$: forbidden state

$(11)_a$: small

Behavior of the flavor-symmetry breaking of the $B_8 B_8$ interaction in the present model (fss2)

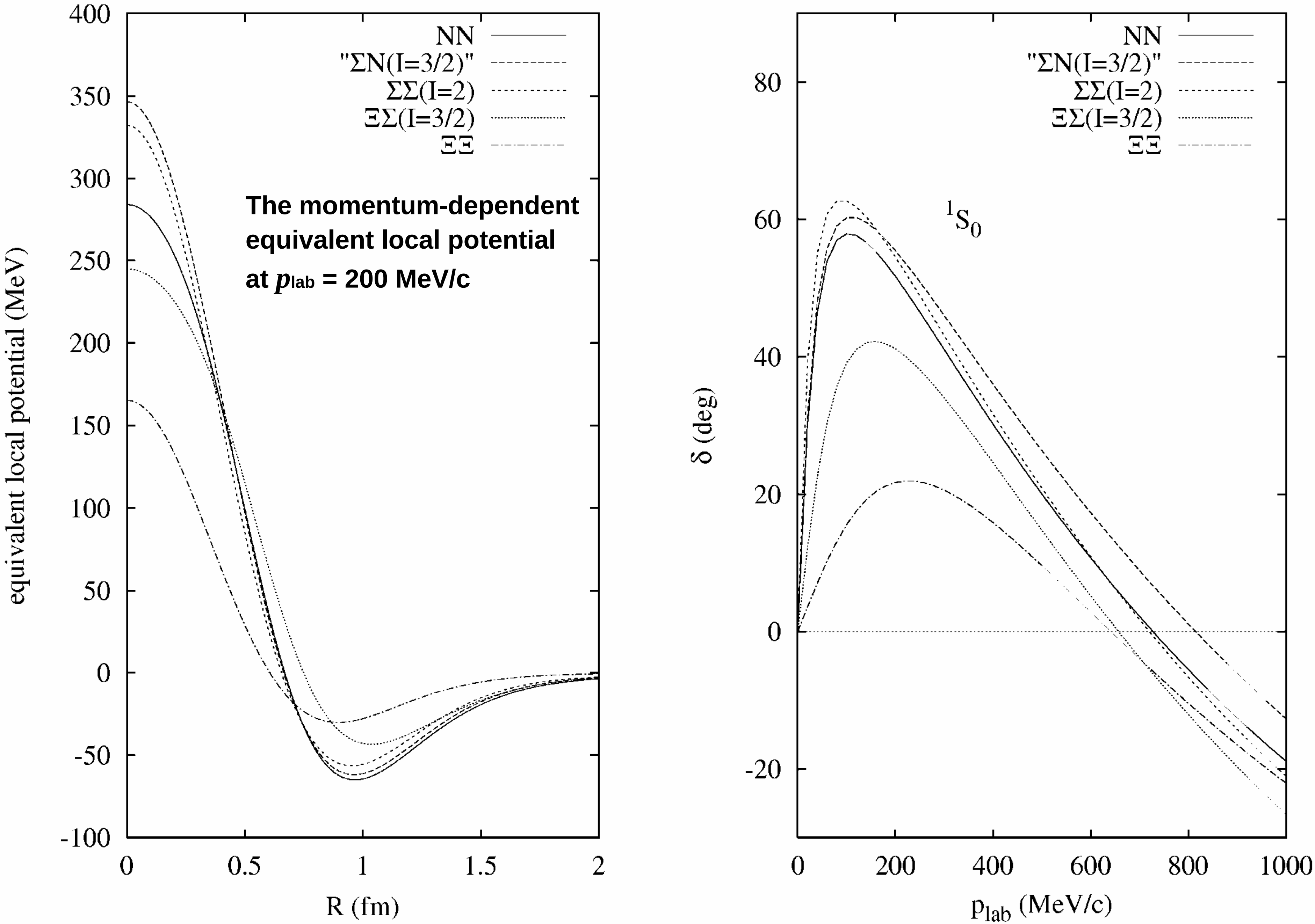
The $B_8 B_8$ interactions generally get weaker as more strangeness is involved.

⇒ Is it the general trend of the SU_6 quark model ?

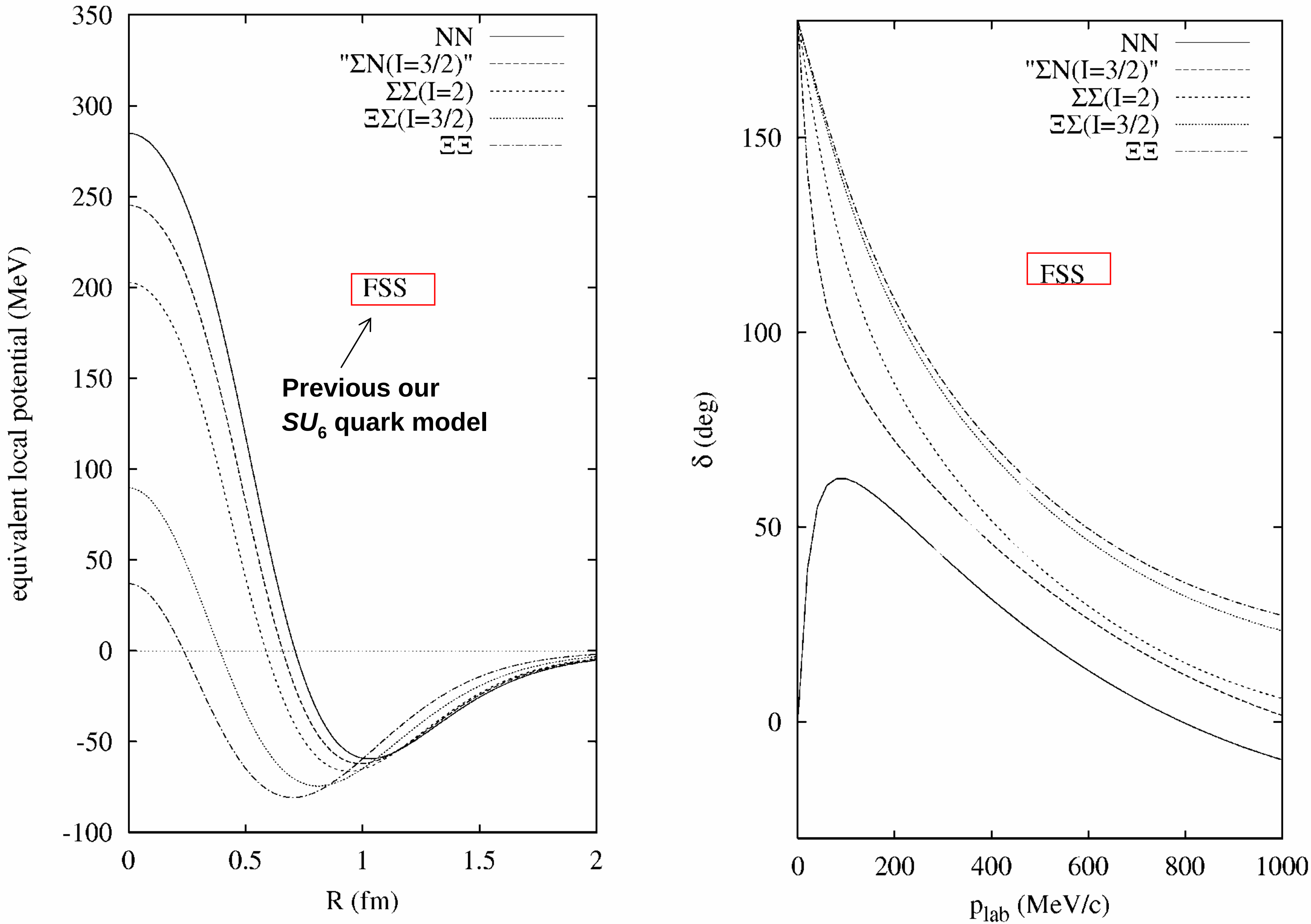
Structure of the B_8B_8 interaction in the SU_6 quark model

Cancellation between the short-range repulsion generated from the color-magnetic term and medium- (and long-) range attraction generated from the EMEP

- They get weaker with increasing the strangeness.
- The feature of the FSB of B_8B_8 interactions is decided by the correlation between the reduction of the repulsion and attraction !



NN
"ΣN(I=3/2)"
ΣΣ(I=2)
ΞΣ(I=3/2)
ΞΞ
The momentum-dependent equivalent local potential at p_{lab} = 200 MeV/c
equivalent local potential (MeV)
R (fm)
$^1S_0$
δ (deg)
p_{lab} (MeV/c)



equivalent local potential (MeV)
R (fm)
NN
"ΣN(I=3/2)"
ΣΣ(I=2)
ΞΣ(I=3/2)
ΞΞ
FSS
Previous our
SU_6 quark model
δ (deg)
p_{lab} (MeV/c)
NN
"ΣN(I=3/2)"
ΣΣ(I=2)
ΞΣ(I=3/2)
ΞΞ
FSS

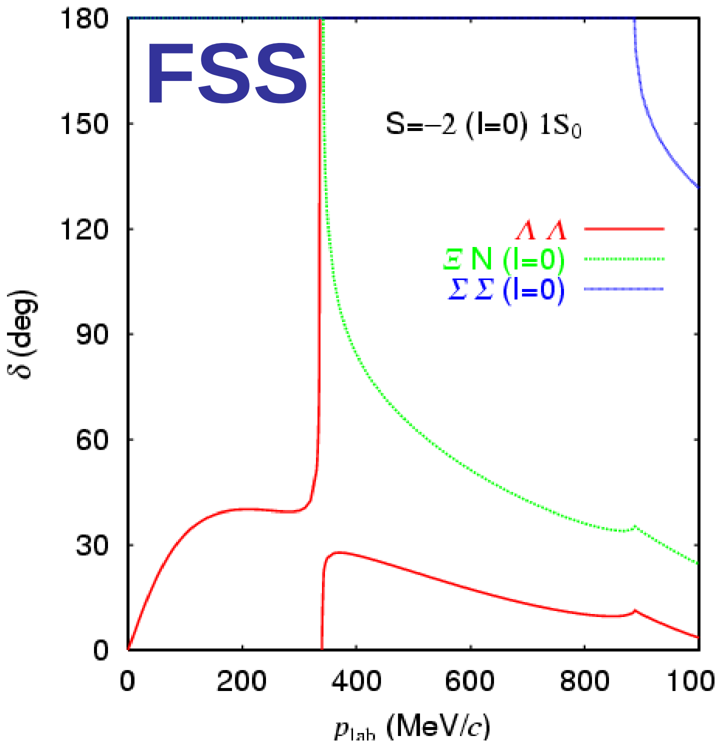
H-dibaryon in the quark model describing the realistic *NN* and *YN* interactions

- Color-magnetic term generates the short-ranged strong attraction in the flavor-singlet (00) state. (by Jaffe)

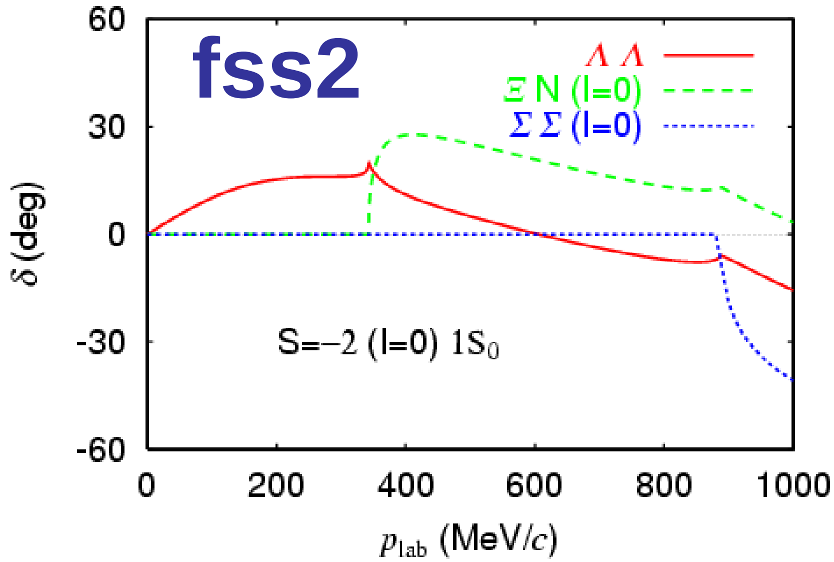
  ΛΛ–ΞN–ΣΣ coupled-channel in $^1S_0$-state

- Coupled-channel calculation only with the FB interaction without FSB
  ⇒ bound state of binding energy 31 MeV
- Coupled-channel calculation only with the FB interaction with FSB
  ⇒ resonance state in the ΛΛ channel
- Coupled-channel calculation with full interactions with FSB
  ⇒ Cancelation between the color-magnetic term and the strangeness meson exchange effect for ΛΛ–ΞN transition potential

S= - 2 *I*=0 phase shifts (H-particle channel)



no bound state below ΛΛ



○ from Nagara event

5. Summary

- We investigated the short-range B_8B_8 interactions in the realistic SU_6 quark model
- Reduction of the repulsion from color-magnetic term at the short-range region and the attraction from EMEP at the medium-range region, with increasing the strangeness
- Feature of B_8B_8 interactions depend on the correlation between them
- No existing H-dibayon in the present model

  ⇒ due to the flavor-symmetry breaking and the strangeness meson exchange effect

Comments

Difference between *pn* and *pp*(or *nn*) interactions in the SU_6 quark model

- [*pn*] = $\frac{1}{\sqrt{2}}$ ([[NN(I=0)] + [NN(I=1)])
- [*pp*] = [*nn*] = [NN(I=1)]

[NN(I=0)] : $^3S_1$, $^1P_1$, ^3D_J, $^1F_3$, …, [NN(I=1)] : $^1S_0$, ^3P_J, $^1D_2$, ^3F_J, …

(1)Quark-Pauli effect : The normalization kernels in the $^1S_0$ and $^3S_1$ states have the same eigenvalues …… no difference

(2)Color-magnetic term : Its repulsion is stronger in the *NN* $^1S_0$-state than in the *NN* $^3S_1$-state.

- simple estimation $< \Sigma\_{i,j} (\lambda_i^c \cdot \lambda_j^c)(\sigma_i \cdot \sigma_j) >$ with the spin-flavor-color wavefunction **Shimizu, RPP52(1989)1**
- equivalent local potential **Suzuki *et al*, PRC27(1983)299**

(3) *LS* term : no contribution in the $^3S_1$ and $^1P_1$ states

Tensor force in the SU_6 quark model

- Origin of tensor contribution in the present model

(1)FB interaction : small

(2) π-exchange effect : large at the long-range region

(3)ρ-exchange effect : partial cancellation of the π-exchange effect

The large contribution of the tensor force to *pn* interaction at the short-range (high-energy) region is unclear in the present model, which is the low-energy effective model.

- effect of higher-momentum term
- multi-gluon exchange effect
- NΔ channel coupling effect

Entem *et al*., PRC62(2000)034002

⇒ The large contribution of attraction even in NN$^1S_0$-state by introducing the coupling to NΔ $^5D_0$-channel