Hyperons in High-Density Nuclear Medium
Is Λ-Σ^0 Mixing is Large or Small?

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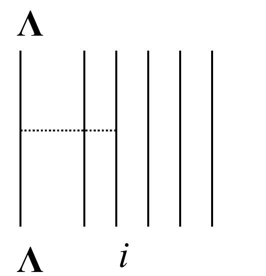
"**Coherent Λ-Σ^0 Mixing**"
in s-Shell Hypernuclei,
in Neutron-rich Hypernuclei,
in Dense Neutron Matter

APFB02

Coherent Λ-Σ^0 Mixing based on the G-Matrix Calculations

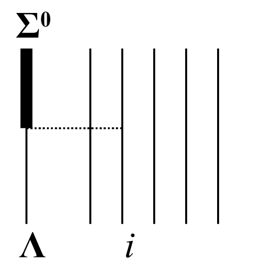
Λ - Nuclear Matter Interaction(lowest order)

$$U_{\Lambda\Lambda} = \langle \mathrm{NM} | \sum_i g_{\Lambda N \Lambda N} | \mathrm{NM} \rangle = \sum_i$$

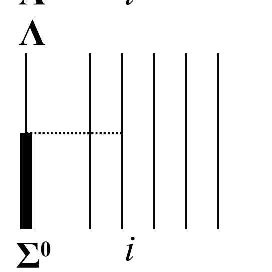


Coherent Λ-Σ coupling

$$U_{\Sigma^0\Lambda} = \langle \mathrm{NM} | \sum_i g_{\Sigma^0 N \Lambda N} | \mathrm{NM} \rangle = \sum_i$$

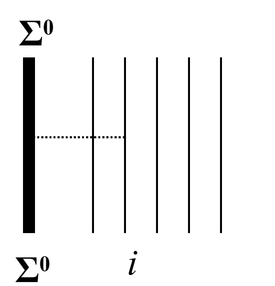


$$U_{\Lambda\Sigma^0} = \langle \mathrm{NM} | \sum_i g_{\Lambda N \Sigma^0 N} | \mathrm{NM} \rangle = \sum_i$$



Off-shell Σ - Nuclear Matter Interaction

$$U_{\Sigma^0\Sigma^0} = \langle \mathrm{NM} | \sum_i g_{\Sigma^0 N \Sigma^0 N} | \mathrm{NM} \rangle = \sum_i$$



Coherent Λ - Σ^0 Mixing by $U_{\Lambda\Lambda}, U_{\Lambda\Sigma}, U_{\Sigma\Lambda}$ and $U_{\Sigma\Sigma}$

$$|\mathrm{Coh}\rangle = (\alpha|\Lambda\rangle + \beta|\Sigma^0\rangle)|\mathrm{NM}\rangle$$

$|\mathrm{NM}\rangle$ = Ground State of Nuclear Matter

$$\begin{pmatrix} \frac{1}{2m_\Lambda}\mathbf{p}^2 + U_{\Lambda\Lambda} + m_\Lambda & U_{\Lambda\Sigma} \\ U_{\Sigma\Lambda} & \frac{1}{2m_\Sigma}\mathbf{p}^2 + U_{\Sigma\Sigma} + m_\Sigma \end{pmatrix}\begin{pmatrix}\alpha \\ \beta\end{pmatrix} = E\begin{pmatrix}\alpha \\ \beta\end{pmatrix}$$

for Λ and Σ with three - momentum $\mathbf{p}$

For $\mathbf{p} = \mathbf{0}$ (Bottom of Fermi sea)

Λ Well Depth : $U_\Lambda = U_{\Lambda\Lambda} + \Delta U$

$$\Delta U = -\frac{1}{2}\left(e + \sqrt{e^2 + 4U_{\Lambda\Sigma}{}^2}\right)$$

Coherent Σ mixing Probability

$$P_{\mathrm{coh.}\Sigma} = \frac{\Delta U^2}{\Delta U^2 + U_{\Lambda\Sigma}{}^2}$$

Where,

$$U_{\mathrm{YY'}} = \langle \mathrm{NM}|\sum_{\mathrm{N}} g_{\mathrm{YNY'N}}|\mathrm{NM}\rangle$$

$$e = (m_\Lambda + U_{\Lambda\Lambda}) - (m_\Sigma + U_{\Sigma\Sigma})$$

Result of G-matrix calculation

Potential:**NSC89** No Proton Mixing

ρ/ρ_0	$U_{\Lambda\Lambda}$ (MeV)	$U_{\Sigma\Sigma}$ (MeV)	$U_{\Lambda\Sigma}$ (MeV)	ΔU (MeV)	$P_{coh\Sigma}$ (%)
0.5	-13.7	2.6	-18.2	**-3.4**	**3.4**
1.0	-20.3	7.6	-34.5	**-10.4**	**8.2**
1.5	-22.4	12.5	-49.6	**-18.8**	**12.6**
2.0	-21.0	18.7	-63.8	**-28.1**	**16.3**
2.5	-16.9	24.8	-77.1	**-38.0**	**19.5**
3.0	-10.4	30.5	-89.8	**-48.4**	22.6

Potential:**NSC97e** No Proton Mixing

ρ/ρ_0	$U_{\Lambda\Lambda}$ (MeV)	$U_{\Sigma\Sigma}$ (MeV)	$U_{\Lambda\Sigma}$ (MeV)	ΔU (MeV)	$P_{coh\Sigma}$ (%)
0.5	-17.3	2.0	-7.1	**-0.5**	**0.5**
1.0	-24.9	6.3	-13.0	**-1.5**	**1.4**
1.5	-26.6	12.2	-18.2	**-2.8**	**2.2**
2.0	-22.6	19.7	-22.9	**-4.2**	**3.3**
2.5	-14.5	28.6	-27.2	**-5.9**	**4.5**
3.0	-2.4	38.9	-31.4	**-7.8**	**5.8**

Coherent Λ-Σ^0 Mixing in Relativistic Mean Field Theory

Lagrangian Density

$$\mathcal{L}=\mathcal{L}_B{}^0+\mathcal{L}_M{}^0+\mathcal{L}_{int}$$

Baryons: n,p,Λ,Σ^0,Σ^-

Mesons: σ,ρ,ω,a

For n,p,Σ^-

$$(p - \gamma^0 g_{BB\rho}\rho_0 - \gamma^0 g_{BB\omega}\omega_0 - m_B+g_{BB\sigma}\sigma+g_{BBa}a)B=0$$

For Λ,Σ^0

$$(p - \gamma^0 g_{\Lambda\Lambda\omega}\omega_0 - m_\Lambda+g_{\Lambda\Lambda\sigma}\sigma)\Lambda -(\gamma^0 g_{\Lambda\Sigma\rho}\rho_0-g_{\Lambda\Sigma a}a)\Sigma^0=0$$

$$(p - \gamma^0 g_{\Sigma\Sigma\omega}\omega_0 - m_\Sigma+g_{\Sigma\Sigma\sigma}\sigma)\Sigma^0 -(\gamma^0 g_{\Sigma\Lambda\rho}\rho_0-g_{\Sigma\Lambda a}a)\Lambda=0$$

For mesons

$$m_\sigma^2\sigma = \sum_B^5 g_{BB\sigma} \langle \bar{B}B \rangle$$

$$m_\rho^2\rho^0 = \sum_B^3 g_{BB\rho} \langle \bar{B}\gamma^0 B \rangle$$

$$+\mathbf{g_{\Lambda\Sigma\rho}(\langle \Lambda\gamma^0\Sigma \rangle + \langle \Sigma\gamma^0\Lambda \rangle)}$$

$$m_\omega^2\omega^0 = \sum_B^5 g_{BB\omega} \langle \bar{B}\gamma^0 B \rangle$$

$$m_a^2 a = \sum_B^3 g_{BBa} \langle \bar{B}B \rangle$$

$$+\mathbf{g_{\Lambda\Sigma a}(\langle \Lambda\Sigma \rangle + \langle \Sigma\Lambda \rangle)}$$

Coupled Channel Dirac Equation

$$[p - g_1 \gamma^0 - m_1]\, \psi_1 - [g_c \gamma^0 + m_c]\psi_2 = 0$$
$$[p - g_2 \gamma^0 - m_2]\, \psi_2 - [g_c \gamma^0 + m_c]\psi_1 = 0$$

$g_1 = g_2 = 1.0321$(**ω** contribution)

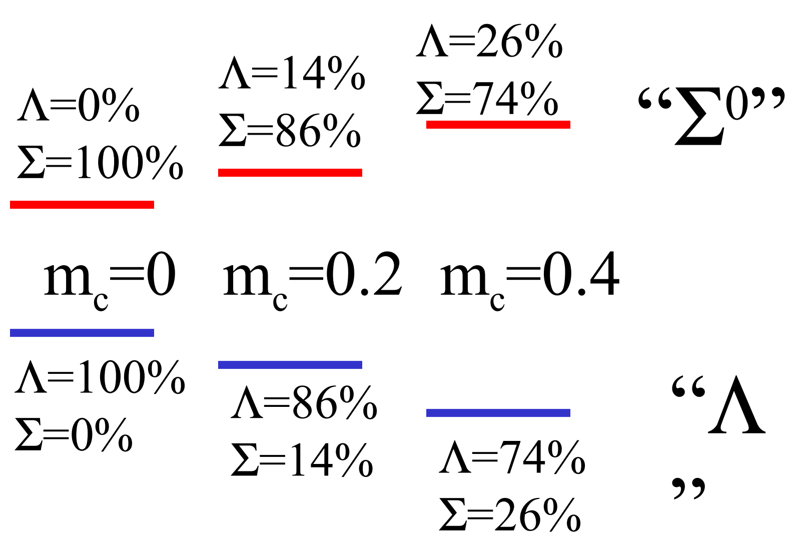
$g_c = 0$(**ρ** contribution, g(**ΛΣρ**)=0)

m_c=a-meson contribution

$m_1 = 4.5278(\Lambda)$, $m_2 = 4.9178(\Sigma^0)$

Energy eigenvalue for three-momentum p=0

m_c	lower solution	upper solution	
0.0	**5.5598**	**5.9498**	
0.2	**5.4754**	**6.0343**	
0.4	**5.3098**	**6.1999**	fm^{-1}



Numerical Result in Relativistic Mean Field Theory

Parameters used here

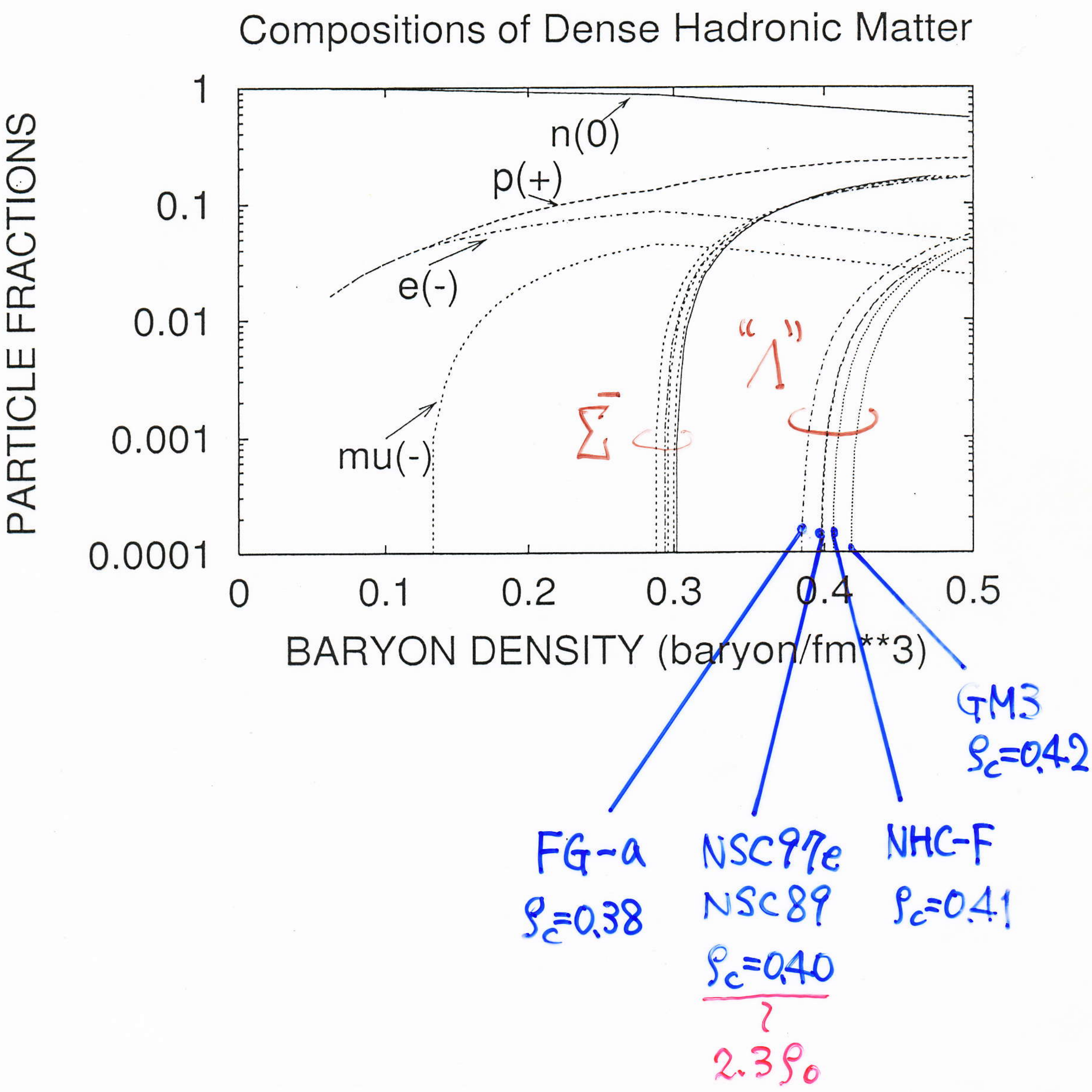
GM3:Saturation properties of
Nuclear Matter

We introduce g(NNa), then
re-adjust g(NNρ) to reproduce
original properties of GM3,
symmetry energy

g(NNa),g(ΛΣa),g(ΛΣρ)←OBEP

	g(NNa)	g(ΛΣa)	g(ΛΣρ)
NSC97e	-4.95	-0.70	0
NSC89	-4.53	-1.49	0
NHC-F	-3.32	-1.90	0
FG-a	-2.70	-6.90	0

Figure 1



Compositions of Dense Hadronic Matter
PARTICLE FRACTIONS
1
0.1
0.01
0.001
0.0001
0
0.1
0.2
0.3
0.4
0.5
BARYON DENSITY (baryon/fm**3)
n(0)
p(+)
e(-)
mu(-)

RMF calc. for various interactions

	ρ_c	$P_\Sigma(\rho_C)$%
NSC97e	0.40	0.26
NSC89	0.40	0.99
NHC-F	0.41	0.89
FG-a	0.38	7.32

As expected,

$$P_\Sigma(\rho_c) \propto [g(\Lambda\Sigma a)g(NNa)]^2$$

Ambiguity in $g(\Lambda\Sigma a)$ is crucial.

Σ^0-Λ Mixing in QCD Sum Rules

by N. Yagisawa, T. Hatsuda, A. Hayashigaki

(Nucl. Phys. A699(2002)665)

$$\theta = \Sigma^0 - \Lambda \text{ Mixing Angle}$$

$$= \theta_0 + \theta^S_{med} + \theta^V_{med}$$

$$\frac{\theta^V_{med}}{\theta^S_{med}} = -\frac{1}{2}\frac{\langle \delta(q^+ q)\rangle_{Med}}{\langle \delta(\bar{q}q)\rangle_{Med}} \cong -\frac{1}{2}\left\{\frac{\delta m}{\delta M_N}\right\}$$

$$\cong -\frac{1}{2}\times\frac{3.9}{2.04} \cong -1$$

where, they used

$$\delta m = m_d - m_u \cong 3.9\text{MeV}$$

$$\delta M_N = (M_n - M_p)^{\text{QCD}} \cong 2.04\text{MeV}$$

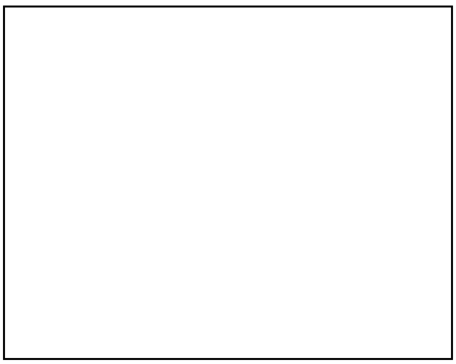
Then, they obtain

$$\theta_{med} = \theta^S_{med} + \theta^V_{med} \cong 0$$

Their quantitative result:

$$\vartheta = \pm(0.01 \pm 0.04)(\rho_n - \rho_p)/\rho_0 + \vartheta_0$$

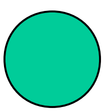
Nuclear Medium in QCD Sum Rules



Vacuum

$$\langle q\, q \rangle_0 = 0$$

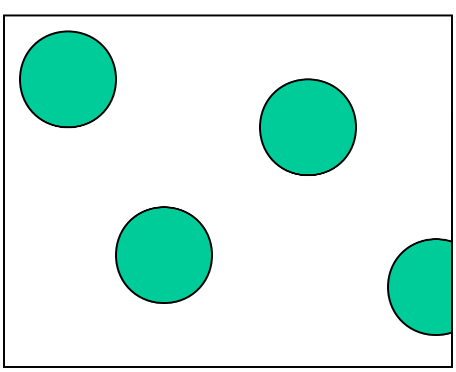
$$\langle \bar{q} q \rangle_0 \neq 0$$



Baryon

$$\langle q\, q \rangle_B \neq 0$$

$$\langle \bar{q} q \rangle_B \neq 0$$



Medium

$$\langle q\, q \rangle_{\mathrm{Med}} = \langle q\, q \rangle_{\mathrm{B}} \rho_B$$

$$\langle \bar{q} q \rangle_{\mathrm{Med}} = \langle \bar{q} q \rangle_0 + \langle \bar{q} q \rangle_{\mathrm{B}} \rho_B$$

Medium = assembly of non-interacting baryons

Comparison at ρ_c

ρ_c=0.40(1/fm^3)=2.3ρ_0
(Critical density of "Λ" appearance)

$\alpha_{np}=(\rho_n-\rho_p)/(\rho_n+\rho_p) \fallingdotseq 0.48$

The case of NSC97e

	OBEP	RMF	QSR
$P_\Sigma(\rho_c)$(%)	2.0	0.26	<0.25*
g(ΛΣa)	-0.70	-0.70	
g(ΛΣπ)	12.1		
g(ΛΣρ)	0	0	
f(ΛΣρ)	9.04		

*=$[\pm(0.01\pm0.04)(\rho_n-\rho_p)/\rho_0]^2$ (Yagisawa et al.)

A Disscusion

$$g(\Lambda\Sigma\rho) = \frac{2}{\sqrt{3}}(1-\alpha_V)g_8 = 0 \text{ for } \alpha_v = 1$$

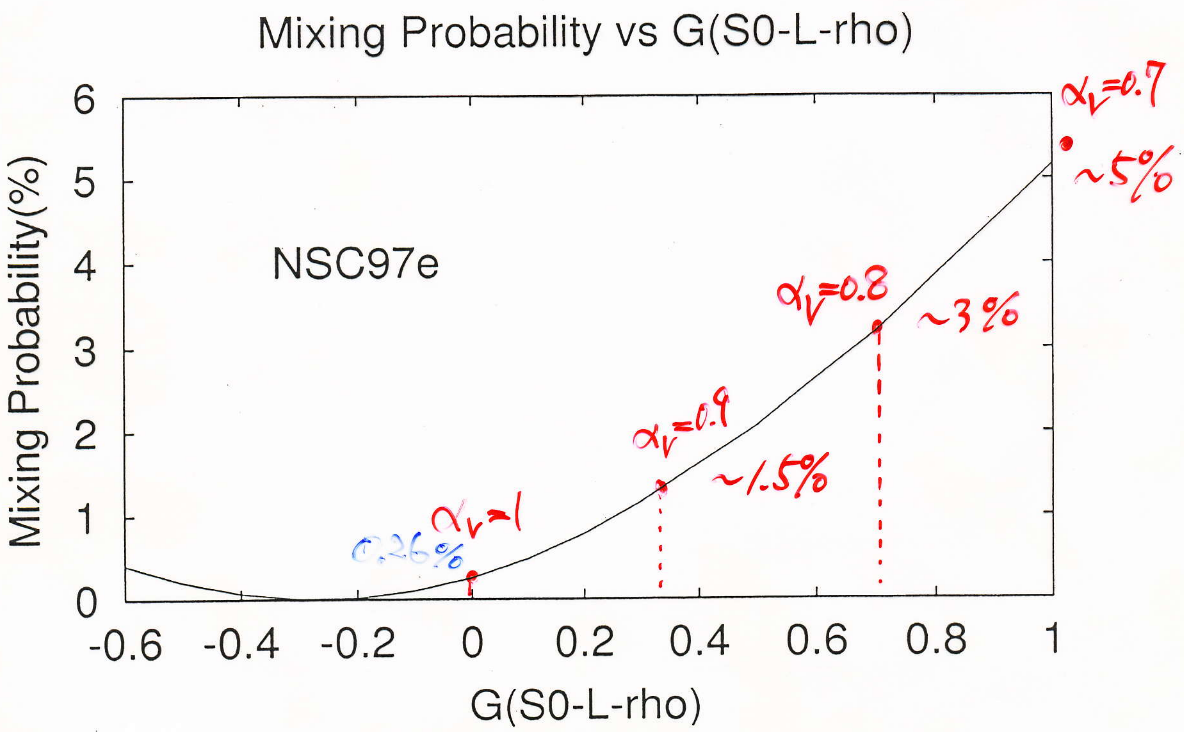
$g_8 = 2.97$ (NSC97a – f, FG – a) $= g(NN\rho)$

$\alpha_V = 1$ is assumed from SU(6) and universal coupling to isospin current(J. J. Sakurai)

If $\alpha_v \neq 1$

α_v	1	0.9	0.8	0.7
$g(\Lambda\Sigma\rho)$	0	0.34	0.69	1.03

Figure 2 RMF calculation



Summary

We dicussed Λ-Σ^0 Mixing in Three Models:

G-Matrix Theory at $\rho_c \sim 2.3\rho_0$

Relativistic Mean Field(RMF) Theory ($\alpha_{np} = 0.48$)

QCD Sum Rules(QSR) Approach

G-Matrix Theory:

Most dynamical among the three.

~~5%-20%~~ 2%~10% Mixing, depending on OBEP

RMF Theory:

Classical static meson fields are introduced

0.2%-7% Mixing, depending

on $g(\Lambda\Sigma a)g(NNa)$, and on $\alpha_V=1$ or $\neq 1$

QSR approach:

Non-interacting baryons

0-0.2% Mixing, depending on $\langle q^\dagger q\rangle$,$\langle \bar{q}q\rangle$ in medium

We believe that **the result of the G-Matrix is most realistic, because it is most dynamical calculation**.

Meson-Baryon Potential
- $K^{bar}N$, $\pi\Sigma$ Scattering Amplitudes -

Gifu Univ., Nihon Univ. and Riken

S. Shinmura, M. Wada, Y. Akaishi and M. Obu

KAON Workshop @ Riken 090511

Our Model of BB and mB potentials

- The One-Hadron-Exchange mechanism
- The SU(3)-symmetric coupling constants
- Mesons and Baryons with Physical Masses and Widths
- Retardation Effect, Velocity-dependence
- Gaussian Source Functions (Form Factors)

Our BB potentials describe interactions between all octet baryon pairs(**From NN to ΞΞ**)

Funabashi-Gifu Potential

GSOBEP

As an extension of our BB potential model, we propose meson-baryon(mB) potentials:

Meson-Baryon Potentials

Mesons:=Pseudoscalar Mesons
Baryons:=Octet Baryons

S= 1 sector: **KN**

S= 0 sector: **πN – ηN – KΛ – KΣ**

S= -1 sector: **$\pi\Lambda$ – $\pi\Sigma$ – $\bar{K}$N – $\eta\Lambda$ – $\eta\Sigma$**

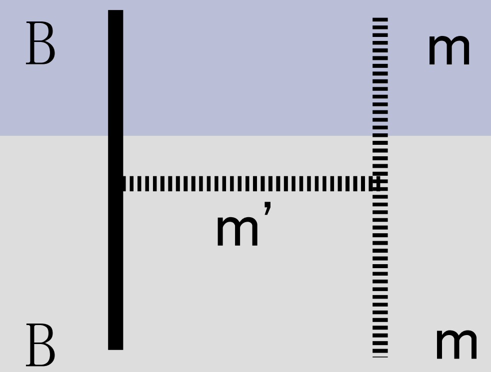
S= -2 sector: **$\pi\Xi$ – $\eta\Xi$ – $\bar{K}\Lambda$ – $\bar{K}\Sigma$**

S= -3 sector: **$\bar{K}\Xi$**

Interaction Mechanisms

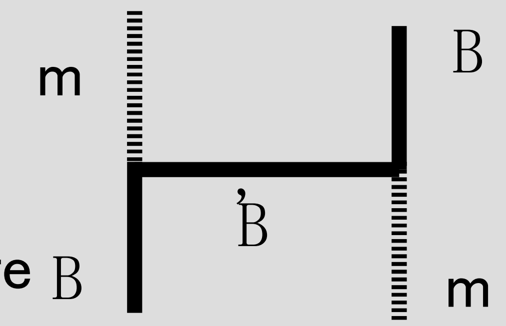
Meson–Exchange Diagrams

Vector–Meson–Exchange
Scalar–Meson–Exchange



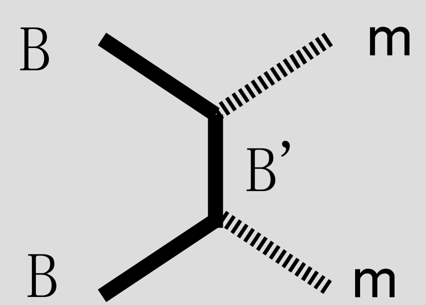
Baryon–Exchange Diagrams

Octet–Baryon Exchange
Baryon–Resonance–Exchange



Baryon–Pole Diagrams

Octet–Baryon Pole
Baryon–Resonance–Pole



Baryon–Pole Diagrams give Separable Potentials

SU(3) model for Baryons and Mesons

1. Octet baryons in the SU(3) model:

$$\Psi_8^B = \begin{bmatrix} \Sigma^0/\sqrt{2}+\Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2}+\Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{bmatrix}$$

2. Octet pseudoscalar mesons in the SU(3) model:

$$\Phi_8^P = \begin{bmatrix} \pi^0/\sqrt{2}+\eta_8/\sqrt{6} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2}+\eta_8/\sqrt{6} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_8 \end{bmatrix}$$

3. Octet scalar mesons in the SU(3) model:

$$\Phi_8^S = \begin{bmatrix} a^0/\sqrt{2}+f_0/\sqrt{6} & a^+ & \kappa^+ \\ a^- & -a^0/\sqrt{2}+f_0/\sqrt{6} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & -\sqrt{\frac{2}{3}}f_0 \end{bmatrix}$$

4. Octet vector mesons in the SU(3) model:

$$\Phi_8^V = \begin{bmatrix} \rho^0/\sqrt{2}+\phi/\sqrt{6} & \rho^+ & K^{*+} \\ \rho^- & -\rho^0/\sqrt{2}+\phi/\sqrt{6} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & -\sqrt{\frac{2}{3}}\phi \end{bmatrix}$$

5. Singlet mesons:

$$\Phi_1^P = \eta', \qquad \Phi_1^S = \sigma, \qquad \Phi_1^V = \omega$$

Interaction Lagrangians in the SU(3) model

Definitions of baryon-baryon-meson coupling constants:

$$\mathcal{L}_{BBm} = g^{(8)}_{m1} \mathrm{Tr}[\bar{\Psi}^B_8 \Phi^m_8 \Psi^B_8] + g^{(8)}_{m2} \mathrm{Tr}[\bar{\Psi}^B_8 \Psi^B_8 \Phi^m_8] + g^{(1)}_{m} \mathrm{Tr}[\bar{\Psi}^B_8 \Psi^B_8] \Phi^m_1]$$

where, $m = P, S, V$.

Definition of meson-meson-meson coupling constants:

$$\begin{aligned}\mathcal{L}_{PPm} \;=\;& g^{(888)}_{PPm1} \mathrm{Tr}[(\Phi^P_8)^\dagger \Phi^P_8 \Phi^m_8] + g^{(888)}_{PPm2} \mathrm{Tr}[(\Phi^P_8)^\dagger \Phi^m_8 \Phi^P_8] + g^{(881)}_{PPm} \mathrm{Tr}[(\Phi^P_8)^\dagger \Phi^P_8] \Phi^m_1] \\ +\;& g^{(818)}_{PPm} \mathrm{Tr}[(\Phi^P_8)^\dagger \Phi^m_8] \Phi^P_1] + g^{(188)}_{PPm} (\Phi^P_1)^\dagger \mathrm{Tr}[\Phi^P_8 \Phi^m_8] + g^{(111)}_{PPm} (\Phi^P_1)^\dagger \Phi^P_1 \Phi^m_1\end{aligned}$$

where, $m = S, V$.

Symmetric(α=0) for PPS α=F/(F+D)

Antisymmetric(α=1) for PPV

Forms of Three-Meson Coupling

ps meson–ps meson–vector meson coupling

$$L = g_{ppv} \phi_v^{\mu} \phi_p \partial_{\mu} \phi_p$$

ps meson–ps meson–scalar meson coupling

$$L = g_{pps} m_{\pi} \phi_s \phi_p \phi_p$$

or

$$L = -\frac{g_{pps}}{m_{\pi}} \phi_s \partial_{\mu} \phi_p \partial^{\mu} \phi_p$$

The latter $\longleftarrow$ Low-energy theorem (Soft pion limit)

p-space Meson-Baryon(mB) Potentials

$$V(p_f,p_i) = V_t(p_f,p_i) + V_u(p_f,p_i) + V_s(p_f,p_i)$$

$V_t(p_f,p_i)$ =meson−exchange diagrams

$V_u(p_f,p_i)$ =baryon−exchange diagrams

$V_s(p_f,p_i)$ =baryon−pole diagrams

$= \Gamma(p_f)\,\Gamma(p_i) / (s - M_B)$ for corresponding p.w.

$= Q(p_f)\,Q(p_i)$ for other partial waves (background contribution)

Renormalization in Baryon-Pole Contributions

$$V(p_f,p_i) = V_T(p_f,p_i) + \Gamma(p_f)\,\Gamma(p_i)\,/\,(s-M_B)$$

$$V_T(p_f,p_i) = V_t(p_f,p_i) + V_u(p_f,p_i)$$

$\Gamma^* = \Gamma + T_T G \Gamma \qquad M_B^* = M_B + \Sigma, \quad \Sigma = \Gamma^* G \Gamma$

Two or more Baryon poles → $\Sigma_{BB'}$: Matrix
(Diagonalization→Baryon mixing)

$$T(p_f,p_i) = T_T(p_f,p_i) + \Gamma^*(p_f)\,\Gamma^*(p_i)\,/\,(s-M_B^*)$$

Results for πN and KN potentials

πN : σ-ex, f_0-ex

ρ-ex

N-ex, Δ-ex, $N^*(1440)$-ex, $S_{11}(1567)$-ex

N-pol, Δ-pol, $N^*(1440)$-pol, $S_{11}(1567)$-pol

KN : σ-ex, f_0-ex, a_0-ex

ρ-ex, ω-ex, ϕ-ex

Λ-ex, Σ-ex, $\Sigma^*(1385)$-ex

Result for πN and KN scatt

πN scattering lengths

	calc	exp
S11	0.2470	0.2473±0.0043
S31	−0.1378	−0.1444±0.0057
P11	−0.2356	−0.2368±0.0058
P31	−0.1333	−0.1316±0.0058
P13	−0.0994	−0.0877±0.0058
P33	0.6254	0.6257±0.0058

fm**(2L+1)

$g_{\pi\pi\sigma}$ = -0.053

$g_{\pi\pi f_0}$ = 0.080

(Very weak σ-ex, f_0-ex)

KN scattering lengths

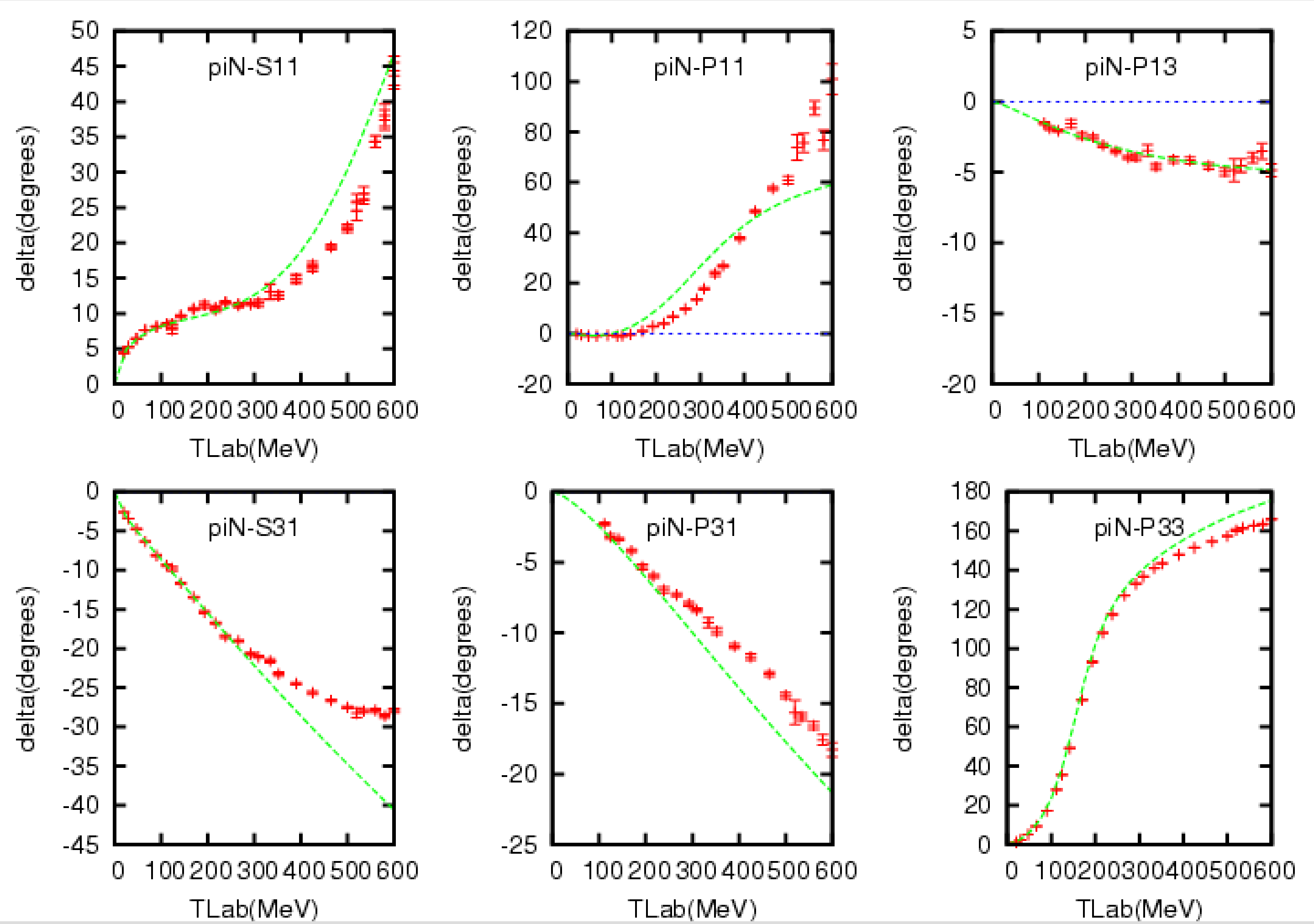
	calc	exp
S01	−0075	+0.00±0.02
S11	−0.353	−0.33±0.02
P01	+0.148	+0.08±0.02
P11	−0.098	−0.16±0.02
P03	−0.006	−0.13±0.02
P13	0.030	+0.07±0.02

fm**(2L+1)

We obtain also
a reasonable fit
for KN.

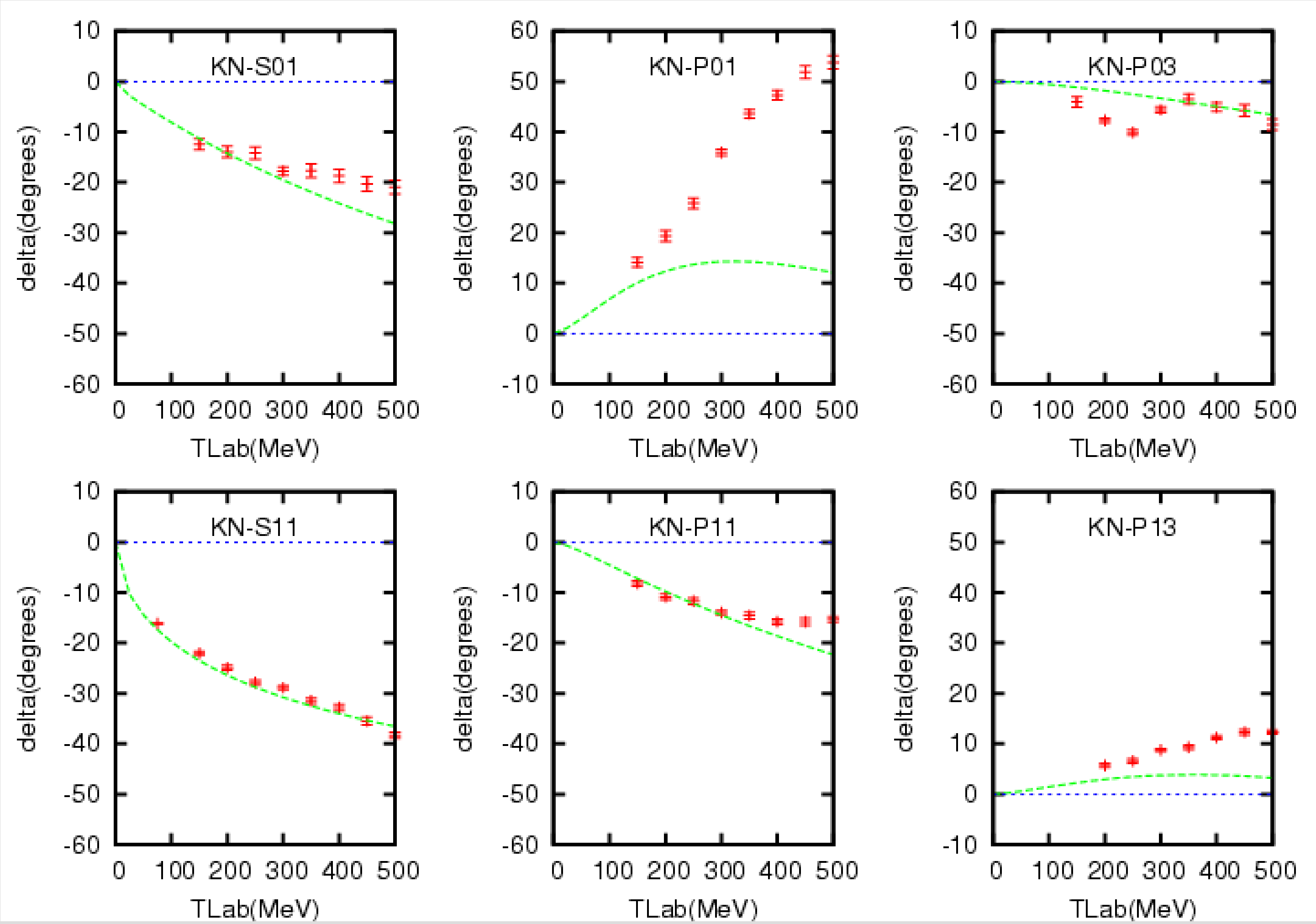
πN Phase Shifts

Exp(single-e) **Calculations**



KN Phase Shifts

Exp(single-e) **Calculations**



$\bar{K}N$ S-wave potential in our model

There is no additional adjustable parameter.
(S-wave $\bar{K}N$ potential is determined by πN and KN potentials.)

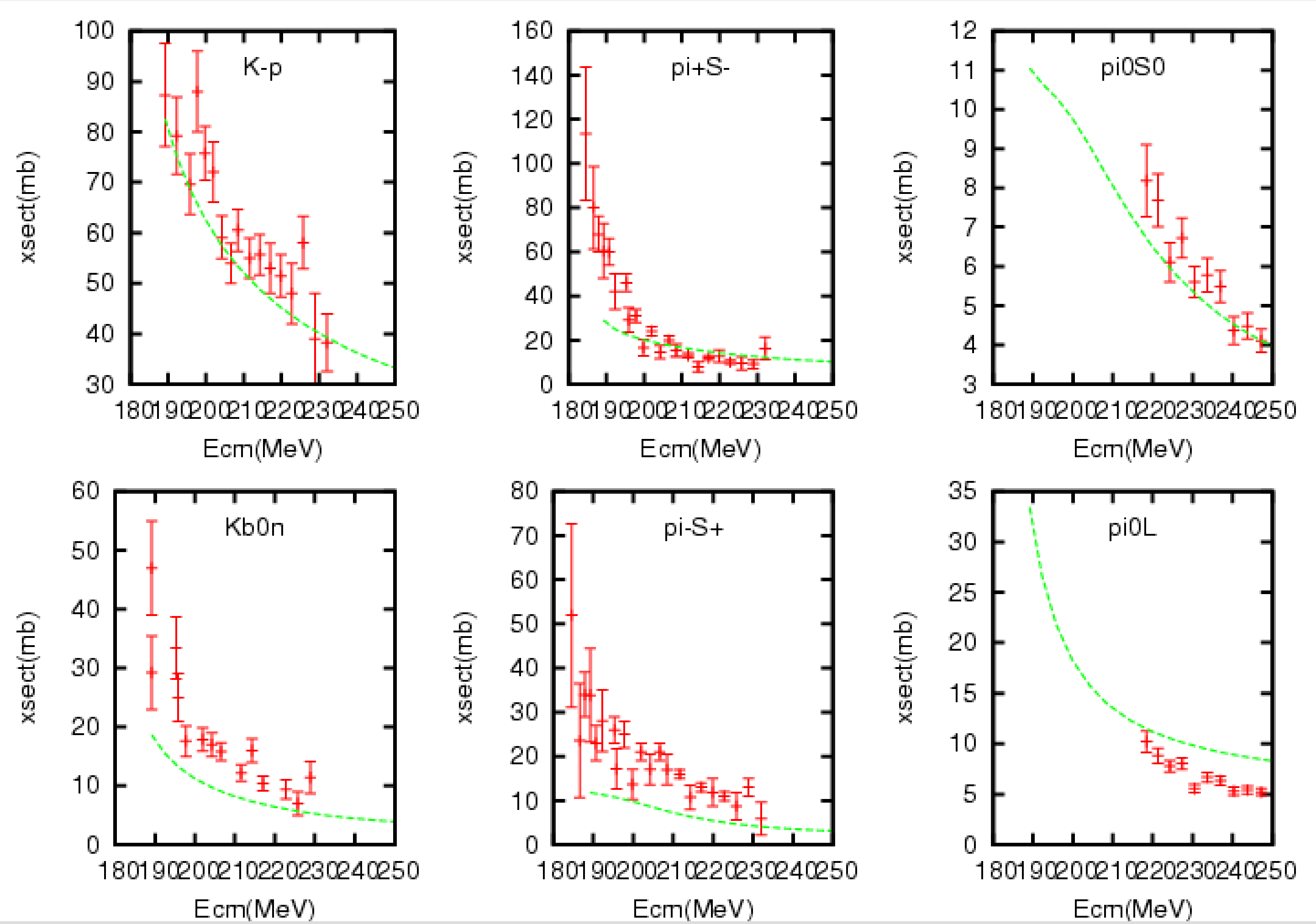
Isospin=0 channels

$\pi\Sigma - \bar{K}N - \eta\Lambda - K\Xi - \eta'\Lambda$

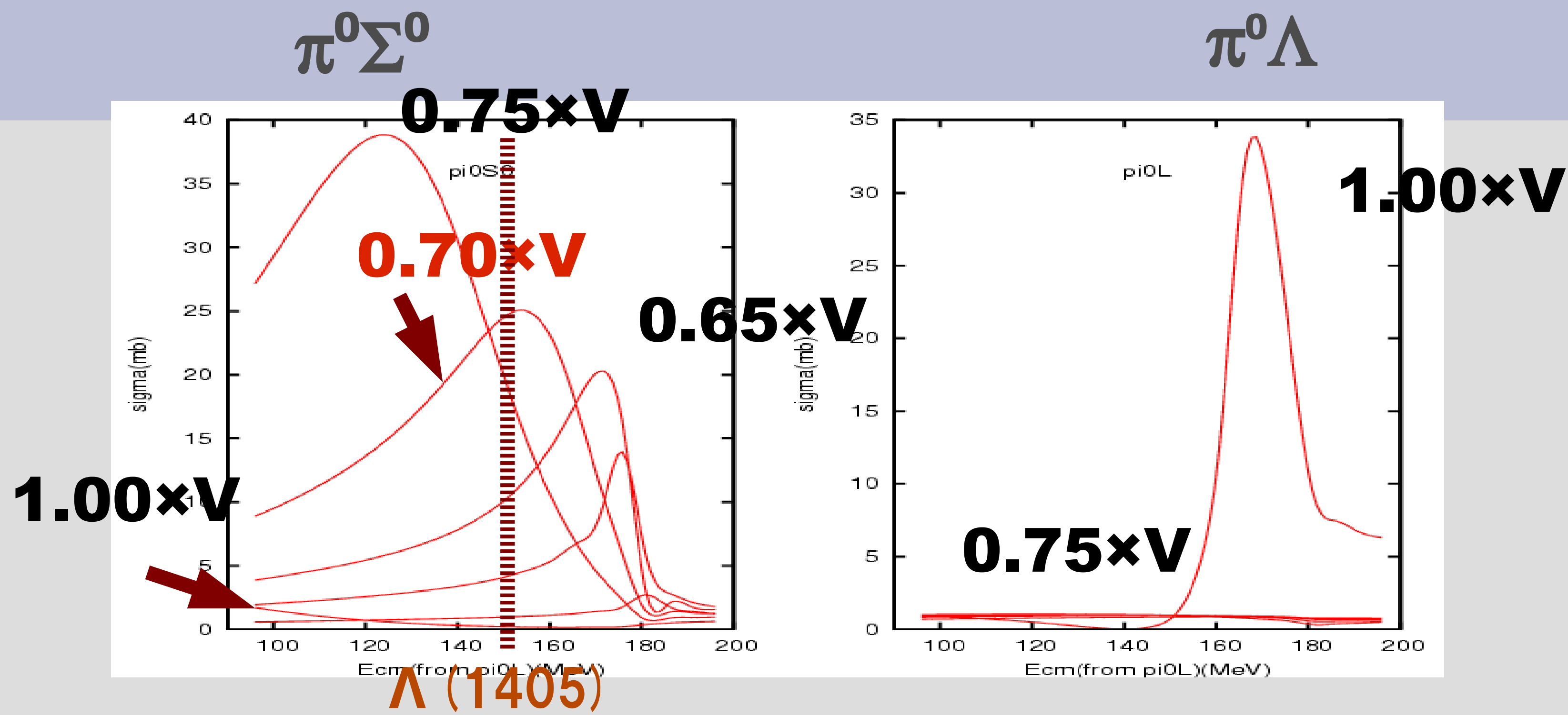
Isospin=1 channels

$\pi\Lambda - \pi\Sigma - \bar{K}N - \eta\Sigma - K\Xi - \eta'\Sigma$

$\bar{K}N$ Reaction Cross sections



$\pi^0\Sigma^0$ and $\pi^0\Lambda$ Elastic Cross Sections(S-wave)



Isospin=0, 2

Isospin=1

Too Strong Attraction! (a factor ～0.7 is needed)
(mainly from ω-ex)

πΣ Mass Spectrum

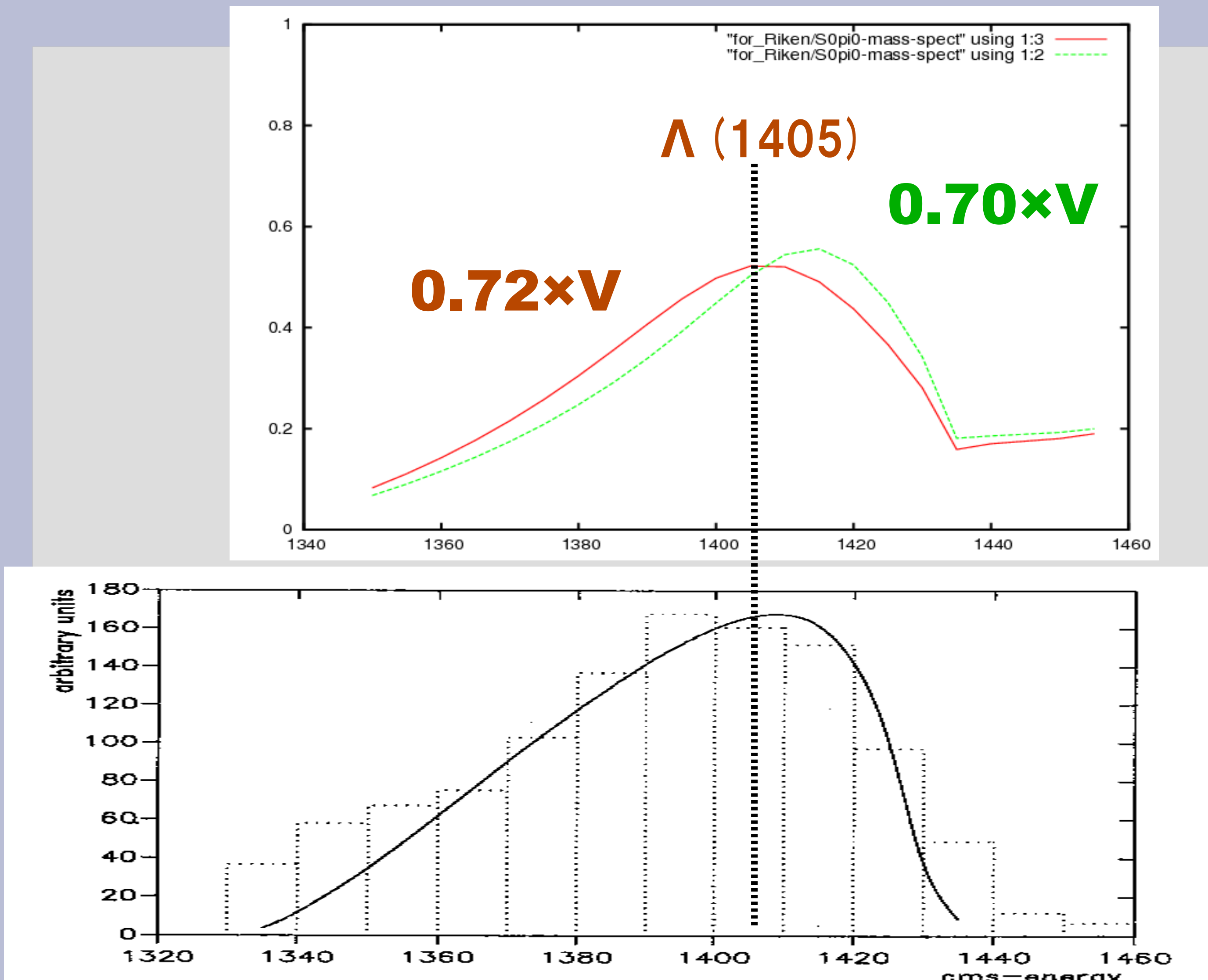
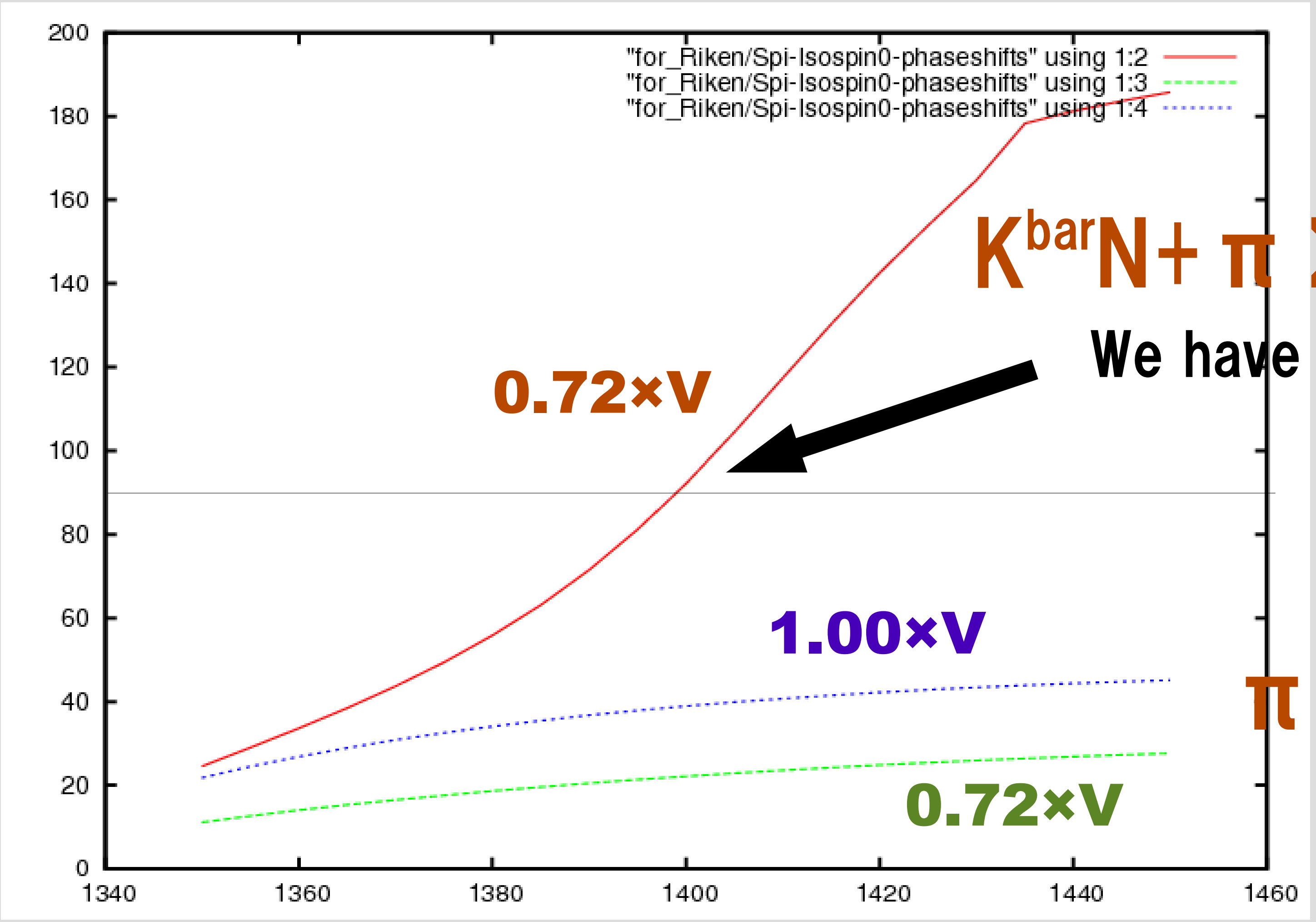


Fig. 6. The Λ(1405) mass spectrum predicted by model II.

Our model reproduce the πΣ mass spectrum by a factor 0.70-0.72.

π Σ S-Wave Phase Shifts (Isospin=0)



$K^{bar}N + \pi\Sigma$

We have a single pole.

$\pi\Sigma$ only

We have no pole.

Summary

○We propose a unified potential model of baryon-baryon and meson-baryon interactions.

○Our model predicts a strongly attractive $K^{bar}N$ potential. Quantitatively, this attraction is too strong to describe Λ(1405).

(0.70-0.72)×V

(All parameters are predetermined by S=0, 1 sectors !)

○Our model reproduce πΣ mass spectrum and we find

Single pole for $K^{bar}N$-πΣ coupled-channel calculation

No pole for πΣ single channel calculation

This pole corresponds to a quasibound state of $K^{bar}N$.

Two- and Three-Baryon Forces in Dense Baryonic Matter

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abstract

Hyperon mixing by two-baryon force(2BF) makes the EOS too soft. But, three-baryon force(3BF) can restore the stiffness of the EOS. 3BF may be essential to sustain the observed masses of neutron stars.

The Equation of State(EOS) of the Dense Baryonic Matter

Observations：

- **Neutron Stars（EOS at low T）**
- **Heavy Ion Collisions(EOS at high T）**

Theoretical Studies：

- **Nonrelativistic G Matrix Theory**
- **Relativistic Dirac Theory**
- **Relativistic Mean Field Theory**

＊If various degrees of freedom are considered, Eos become too soft.

＊Prof Takatsuka:“Extra repulsion”

＊Uncertainties in theories prevent us to obtain conclusive result.

Nonrelativistic G-Matrix Calculations

* G-Matrix theory can explain successfully the nuclear matter with realistic NN force. (quantitatively, NNN force is needed)
* Realistic two-baryon forces which reproduce NN, YN scattering and hypernuclei are available.

At high densities

* Relativistic effects become important.
* Independent-pair-scattering picture become doubtful.

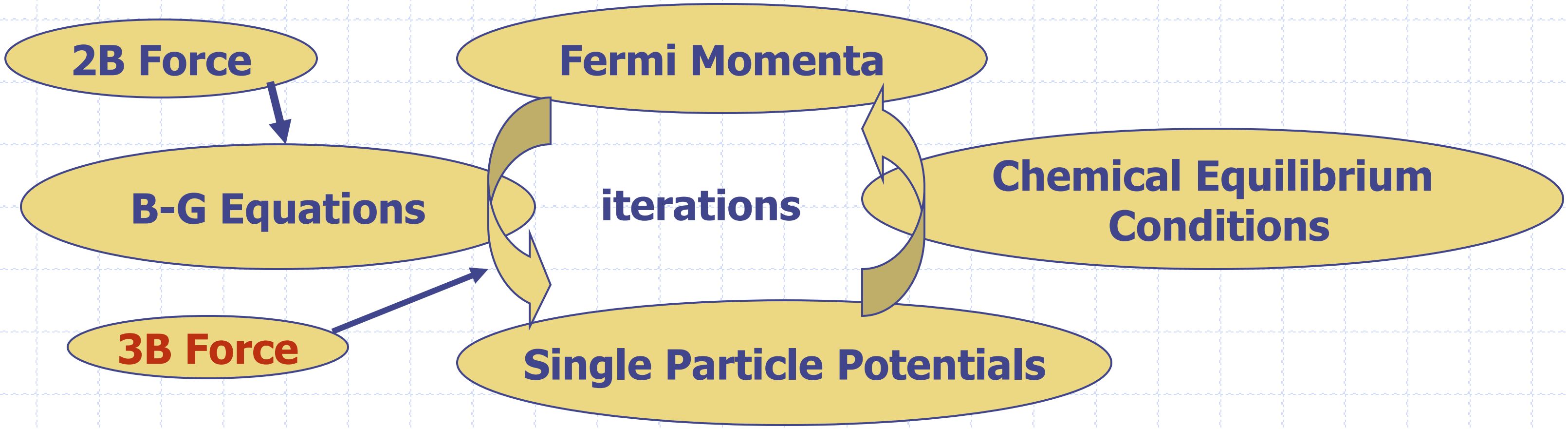
To check the applicability of the G-matrix theory for high-density baryonic matter is an important and interesting problem.

Equilibrated G-Matrix Calculations

The G-matrix combined to Chemical Equilibrium(CE)

Conventional G-Matrix Calc. : Fixed Baryon Compositions
N=Z(Symmetric)Nuclear Matter, (Z=0)Pure Neutron Matter
Fermi Momenta for baryons are fixed in calculation.

Equilibrated G-Matrix Calc.:
Only total baryon density is fixed(conserved).
Depending on Fermi momenta of baryons, the B-G equations determine the single particle potentials.
Depending on the single particle potentials, the CE conditions determine the Fermi momenta of baryons.



Chemical Equilibrium Conditions

under Charge Neutrality and Baryon Number Conservation

$\mu_B = m_B + k_{FB}^{2}/2m_B + U_B(k_{FB})$ for baryons

$\mu_e = [m_e^2+k_{Fe}^2]^{1/2}$, $\mu_\mu = [m_\mu^2+k_{F\mu}^2]^{1/2}$ for e^-, μ^-

Equilibrium Conditions: (8 conditions)

$\mu_B = \mu_n - Z_B\mu_e$ (Z_B=chage of octet baryon B)

$\mu_\mu = \mu_e$

Charge Neutrality:

$\copyright_{\mathbf{B}}\, Z_B k_{FB}^3 - k_{Fe}^3 - k_{F\mu}^3 = 0$

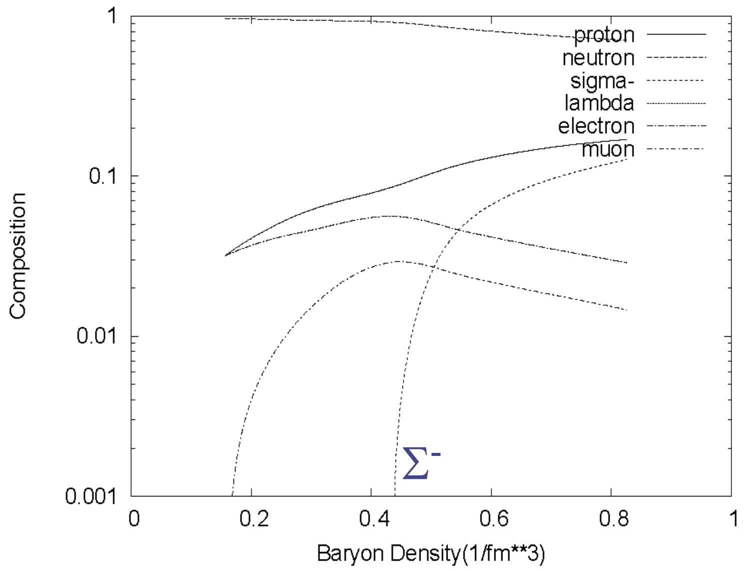
Baryon Number Density:

$\rho_B = \copyright_{\mathbf{B}}\, k_{FB}^3/3\pi^2$

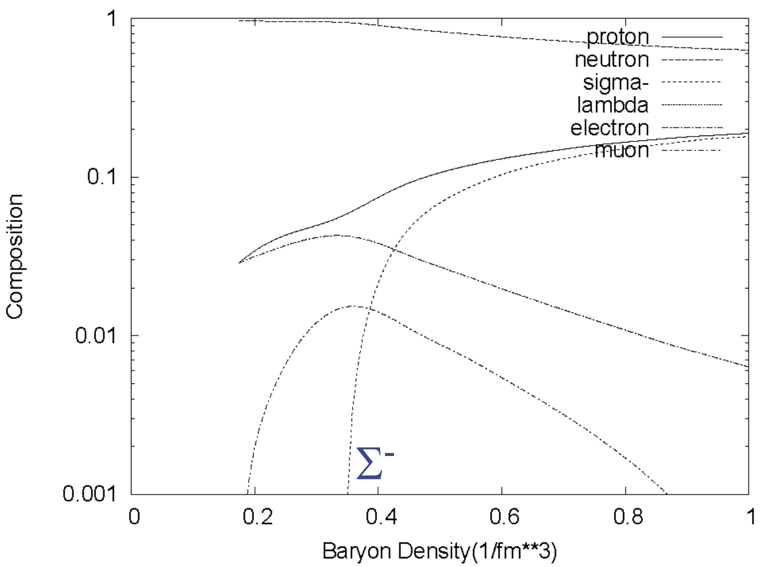
10 Fermi Momenta are determined by 10 conditions.

Compositions of Equilibrated Baryonic Matter with NN,YN,YY Interaction

NSC89



NSC97e



We find a large difference in the threshold density of Σ^- appearance between NSC89 and NSC97e

Generalized 3-Baryon Force(3BF)

Generalized Δ-mechanism

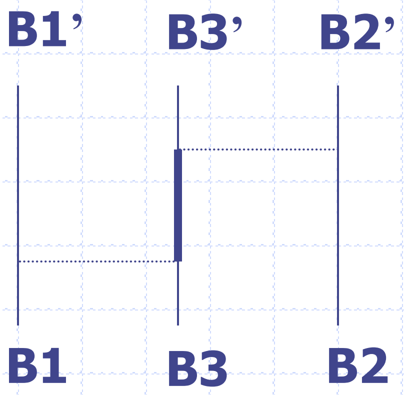
Δ → Decuplet Baryons

π → nonet mesons

SU(3) symmetric interaction Lagrangian

long range part of 3BF

We found Weak Attractive Contribution.



Phenomenological 3BF

UIX, UVII : 2π + short range 3NF

→ short-range part of 3BF

We assume here(a big assumption!)

V(nnn)=V(ppp)=V(BBB)

V(npp)=V(nnp)=V(BBB')

V(BB'B'') = unknown

Contributions of 3BF to Energy-Density and Single Pareticle Potentials

$$\Delta\varepsilon(3BF) = e_3 \sum_{b} \rho_b^{\,3} + e_2 \sum_{b \neq b'} \rho_b^{\,2} \rho_{b'} + e_1 \sum_{b \neq b' \neq b''} \rho_b \rho_{b'} \rho_{b''}$$

e_3=0.6-0.9, e_2=0.3-0.8, e_1=unknown

Saturation properties of nuclear matter

by A.Akmal et al

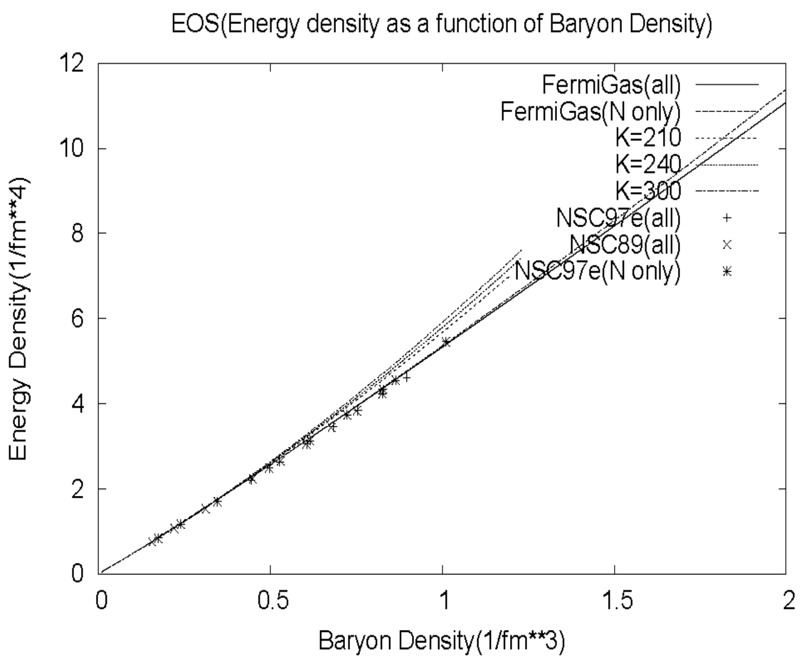
R.B.Wiringa et al.(variational calculations)

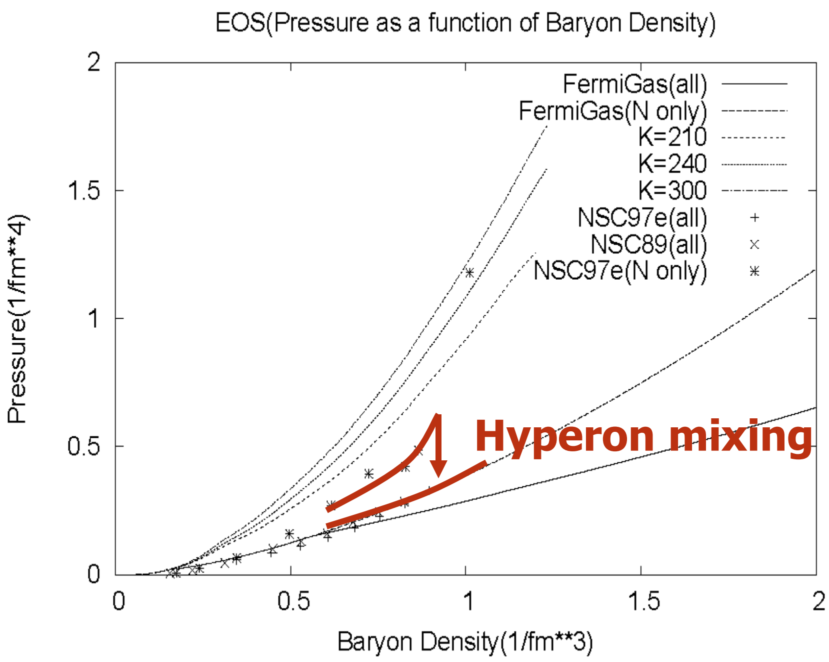
We assume $e_3=e_2=e_1=0.8$ (fm^5) as a trial case.

Single Particle Potentials:

$$\Delta U_B(3BF) = \partial(\Delta\varepsilon(3BF)) / \partial\rho_B$$

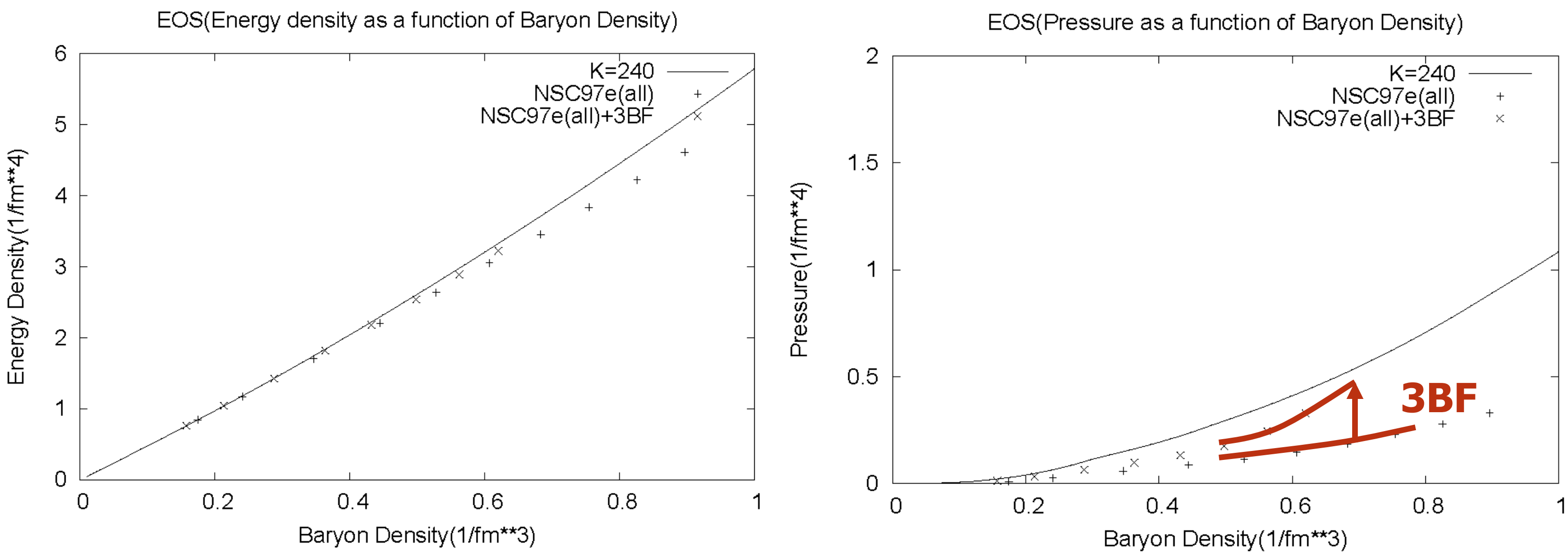
EOS with Only 2BF(NSC89, NSC97e)





We find only small differences in energy densities among models. but large difference in pressure. Hyperon mixing reduces the pressure(EOS becomes softer).
K=210,240,300 are RMF calc. by Glendenning et al.

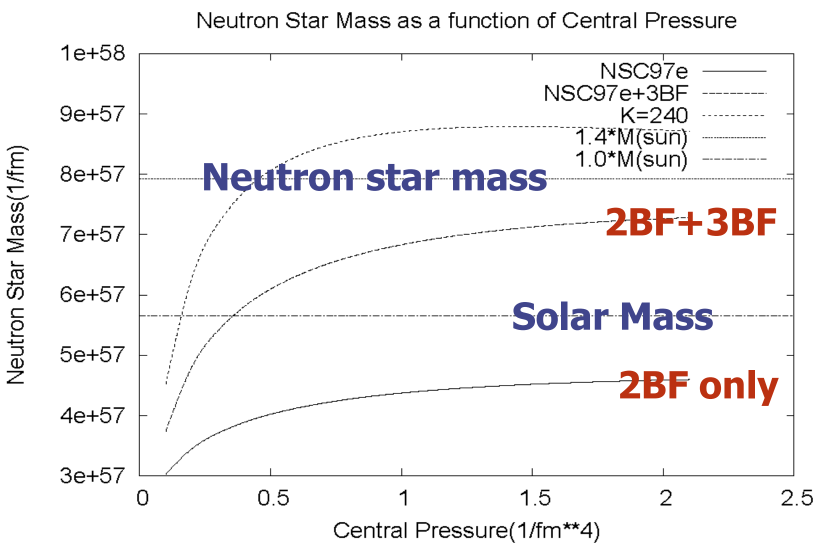
EOS with 2BF and 3BF(NSC97e+3BF)

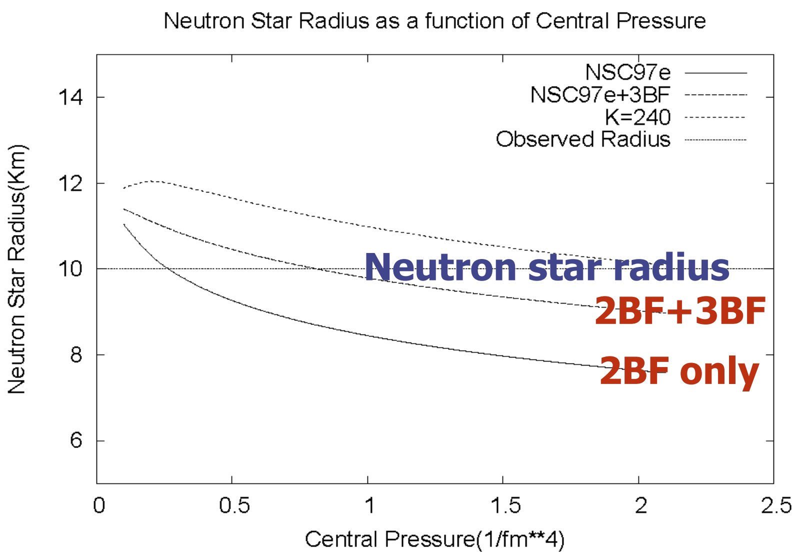


3BF has a large effect on pressure at high densities
3BF increases pressure(EOS becomes stiffer).

Masses and Radii of Neutron Stars

By solving the TOV Equation using EOS, we determine masses and radii of neutron stars as functions of central pressure(or central baryon density)





Only 2BF(NSC97e), EOS can sustain 0.7 times of the solar mass(Ms) at most（EOS is too soft）. But, If we assume 3BF, EOS can sustain around 1.3 times of Ms, which is almost the observed masses(1.4Ms) Short-range repulsive 3BF is essentially important. Radius is also reasonable.

Summary

- **We performed *Equilibrated G-Matrix Calculation* to determine the EOS of Neutron-Star Matter.**
  - **2BF(NSC97e and NSC89)+3BF**
  - **Hyperon mixing**
- **Only 2BF predicts too soft EOS by Hyperon mixing.**
- **We introduce a phenomenological 3BF determined so as to respoduce saturation properties of nuclear matter.**
- **By the 3BF, the EOS becomes stiffer and sustain almost the observed masses of neutron stars.**
- **The theoretical derivation of short-range repulsive 3BF is the most important problem in future.**