Equilibrated Self-Consistent Calculation of Neutron Star and Generalized 3-Baryon Forces

S. Shinmura and Y. Akaishi

Gifu University, JAPAN

KEK, JAPAN

EOS of Dense Baryonic Matter

Phenomenological studies

- **Observed Properties of Neutron Stars(at low T)**
- **Relativistic Heavy Ion Collisions(at high T)**

Theoretical studies at low T

- **Non-relativistic G-matrix Calculations**
- **Relativistic Dirac Approach**
- **Relativistic Mean Field Approach**
  - **Theoretical EOS may be too soft at low T**

The G-matrix Calculations

Realistic Two-baryon Interactions

Well-established at around Normal Density

Merits

Relativistic effects

Demerits

Many-body forces

Applicability at High Baryon Densities

One of the necessary conditions of the applicability:

Three-body forces can be treated as perturbation

G-matrix calculations provide realistic results at up to 4-5ρ_0

By only this method, we cannot discuss the whole of neutron star.

Self-Consistency in baryonic matter calculation

For a given set of densities for constituent baryons,

the single particle potentials(SPP) are determined by the solutions of the B-G equations which depend on SPP. (only the strong interaction is considered)

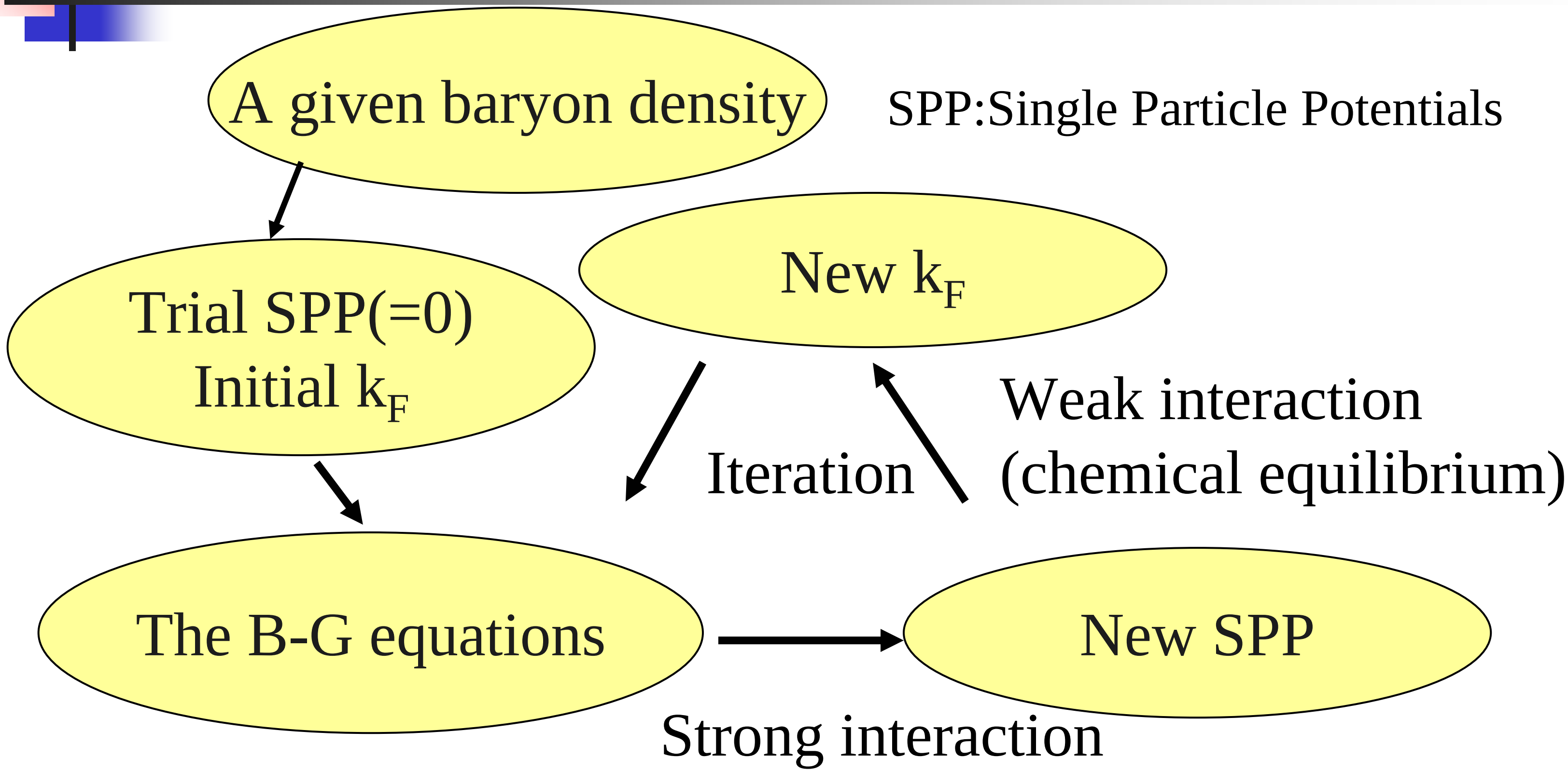
For a given total baryon number density,

baryon compositions are determined by chemical equilibrium, depending on SPP. SPP for each baryon is determined by the B-G equation which depends on both baryon compositions and SPP.

Equilibrated G-matrix calculation

A calculating method(not a new theoretical approach)

Equilibrated G-matrix calculation



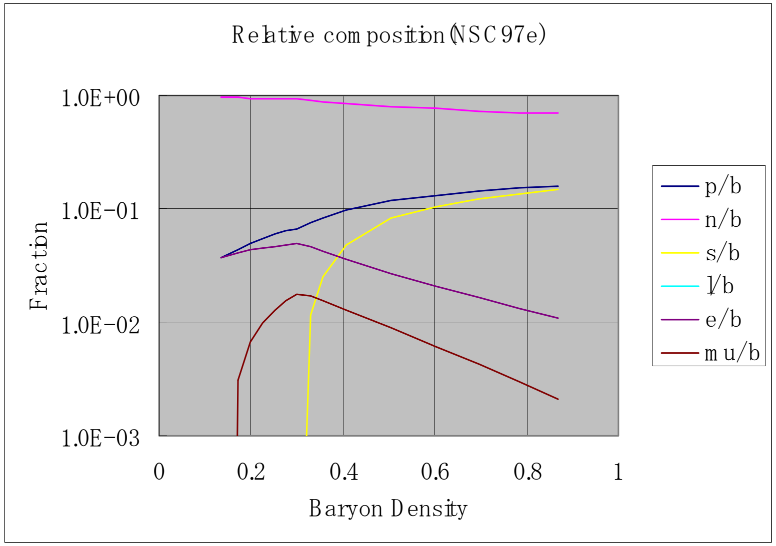
At all densities, SPP for all baryons at bottom of Fermi sea are calculated. It is essential to determine correct thresholds of appearance of baryons.

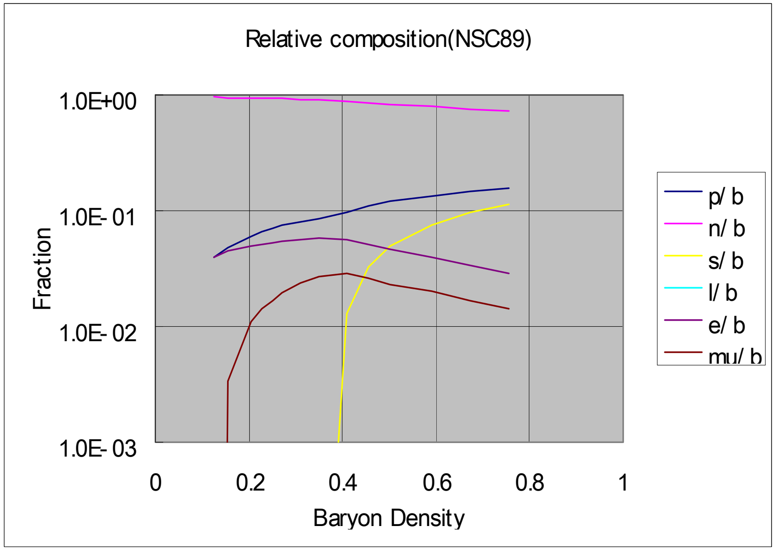
Results of Calculations

Compositions of Equilibrated Baryonic Matter

NN,YN,YY interactions:

NSC97e NSC89

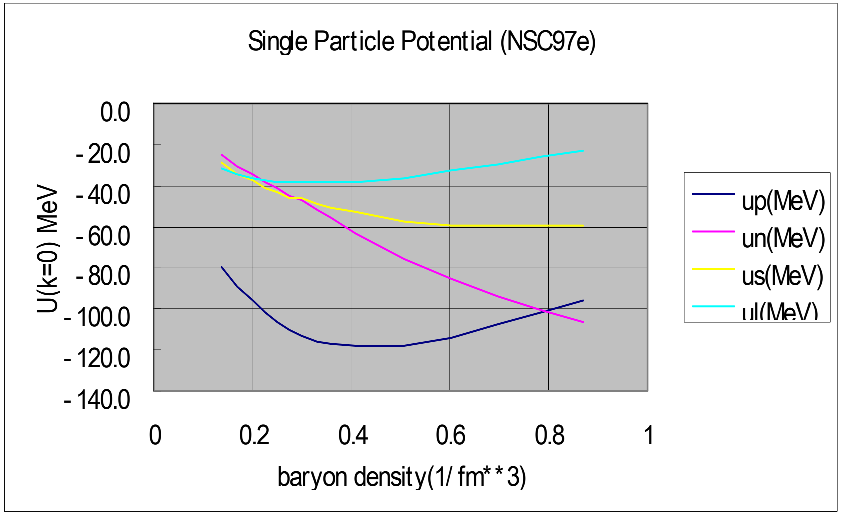




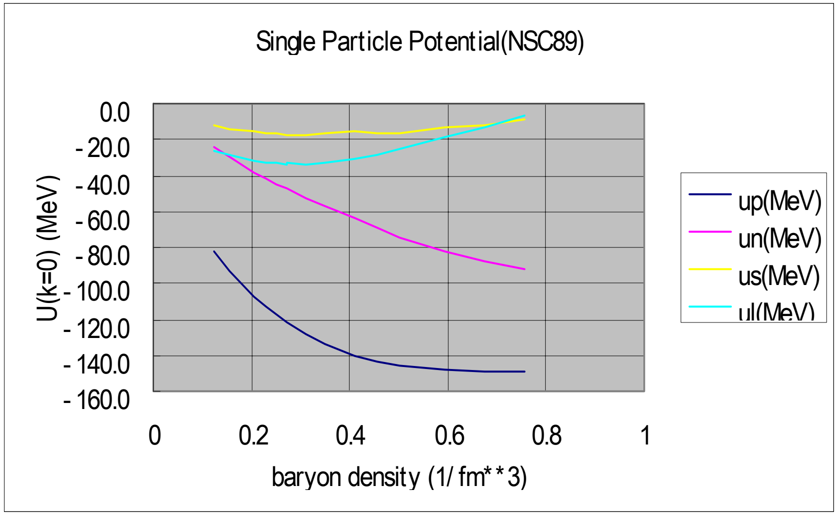
Single Particle Potentials in Equilibrated Baryonic Matter

NN,YN,YY interactions:

NSC97e



NSC89



The point is that this method calculates the compositions and single particle potentials for all species in baryonic matter simultaneously.

Generalized 3-Baryon Forces

NNN 3-body force has a long history

Fujita-Miyazawa force

Brazil model(H.T. Coelho, T.K.Das, M.R. Rabilotta;
M.R. Rabilotta, M.P.Isidro Filho)

Tucson-Melbourne model(S.A.Coon et al.;
B.G. Ellis, S.A.Coon, B.H.J. McKellar)

Phenomenological pion-nucleon scattering amplitudes

Δ mechanism, ρ-meson exchange mechanism

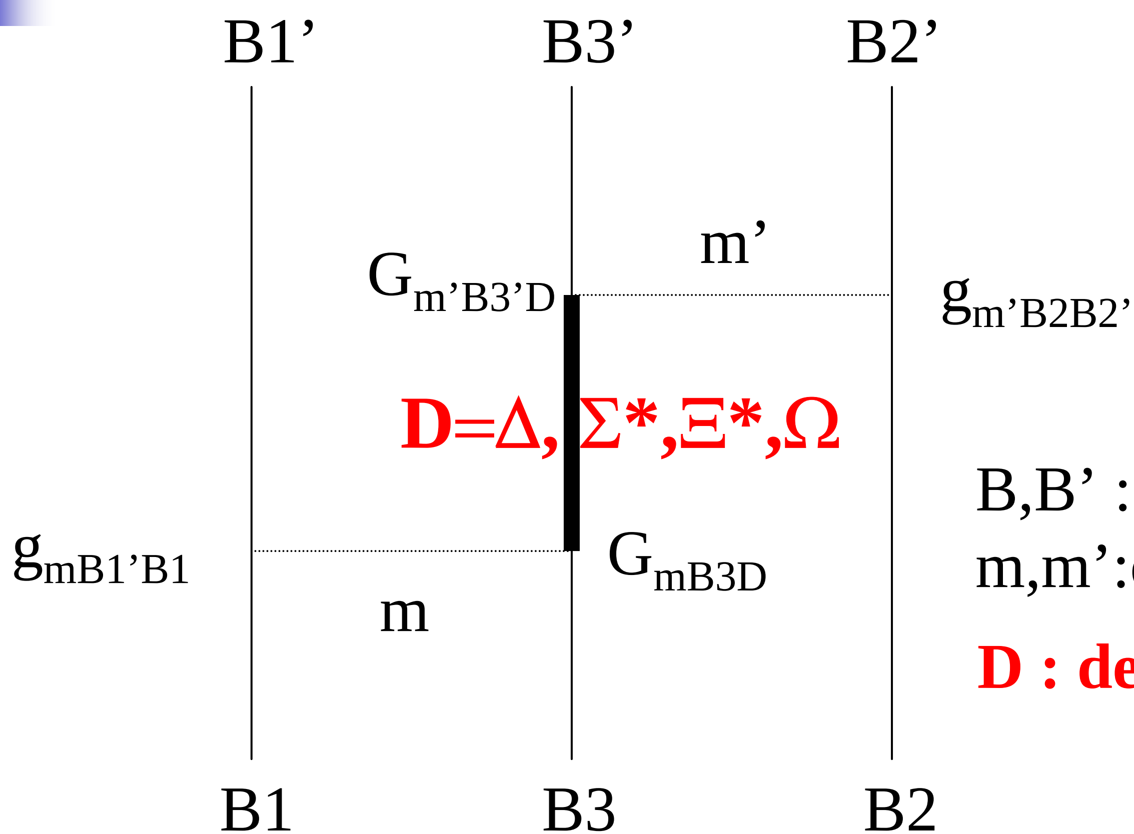
BBB 3-Body Forces in high-density baryonic matter

Phenomenological approach is difficult.

Model-dependent approach is available.

(The SU(3) model)

Generalized Δ-mechnism



B,B' :octet baryons
m,m':octet mesons
D : decuplet baryons

G_{mBD} and $g_{mBB'}$ satisfy the SU(3) symmetry

3BF in static approximation

$$a = \frac{2}{3}\frac{2M_\Delta + M_3 + M_3^{'}}{2M_\Delta^2 - M_3^2 - M_3^{'2}} + \frac{(M_3^2 - M_3^{'2})^2}{12M_\Delta^2}\frac{2M_\Delta + M_3 + M_3^{'}}{(2M_\Delta^2 - M_3^2 - M_3^{'2})^2}$$

$$b = -\frac{1}{12}\frac{2M_\Delta + M_3 + M_3^{'}}{2M_\Delta^2 - M_3^2 - M_3^{'2}}\frac{(M_3 + M_3^{'})^2}{M_3 M_3^{'}} + \frac{(M_3 - M_3^{'})^2 (M_3 + M_3^{'})^2 (2M_\Delta - M_3 - M_3^{'})}{48 M_\Delta^2 M_3 M_3^{'} (2M_\Delta^2 - M_3^2 - M_3^{'2})}$$

$$G = \frac{(M_1 + M_1^{'})^2 (M_2 + M_2^{'})^2}{12 M_1 M_1^{'} M_2 M_2^{'}} G_{m'B3'\Delta} G_{mB3\Delta} g_{mB1'B1} g_{m'B2B2'}$$

$$W(1,2;3) = -G\frac{\overline{m}\,\overline{m}'}{(4\pi)^2}(\sigma_1 \cdot \nabla_{31})(\sigma_2 \cdot \nabla_{23})\{a(\nabla_{31} \cdot \nabla_{23}) + b\, i\sigma_3 \cdot (\nabla_{31} \times \nabla_{23})\}U(\overline{m}, r_{31})U(\overline{m}', r_{23})$$

$$\overline{m} = (m^2 - (M_1 - M_1^{'})^2)^{1/2}, \qquad \overline{m}' = (m'^2 - (M_2 - M_2^{'})^2)^{1/2}$$

Effective meson mass (< Free mass)

Λ= 5.0fm^{-1}(=986.6MeV)

SU3-Model for Meson-Octet-Decuplet Coupling

Phenomenological evidence for the SU(3) model

N.P. Samios, M. Goldberg and B.T. Meadows

Rev. Mod. Phys. Vol.46, p49, 1974.

The SU3-Model for Meson-Octet-Decuplet Coupling is confirmed.

10 irreducible representation:

$$T_{[ab]}^{(cd)} = \psi_{[a}^{(c} \varphi_{b]}^{d)} - \text{(Trace part)}$$

(cd):symmetrized [ab]:antisymmetrized

$$L_{int} = -G\ \Psi^{(abc)} \varepsilon^{(akl} T_{[kl]}^{(bc))}$$

Ψ : decuplet baryons, ψ : octet baryons, φ : octet mesons

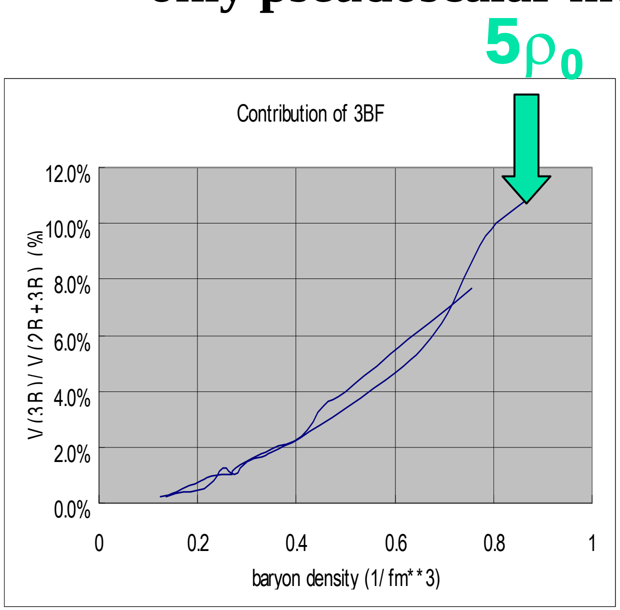
Contribution of 3BF to potential energy density

R = V(3BF)/V(2BF+3BF)≒ 1 % ~ 1 0 % for $2\rho_0 \sim 5\rho_0$

V(3BF) $\propto \rho_{B1}\rho_{B2}\rho_{B3}$ **rapidly increases with densities**

But the results shown here is very preliminary:

Only lowest order and only S-wave contributions,
only pseudoscalar mesons are considered.



Components of 3BF at $5\rho_0$
(NSC97e)

ppn	15.4 %	
pnn	64.8 %	NNN:80.2 %
$pn\Sigma^-$	5.2 %	
$nn\Sigma^-$	12.3 %	YNN:17.5 %
$n\Sigma^-\Sigma^-$	2.3 %	YYN:2.3 %

‘nnn’ is omitted here!

Summary

- A New Calculating Method

  Equilibrated G-matrix calculation, which determines the compositions and SPP simultaneously.

- Generalized 3-Baryon Forces

  Decuplet baryon excitation <- the SU(3) model

  Very preliminary result:

  $V(3BF)/V(2BF+3BF) = 1\text{-}10\%$ for $2\text{-}5\rho_0$

  only S-wave +higher partial waves, nnn

  lowest order +next order

  pseudoscalar +vector mesons

Chemical Equilibrium, Charge Neutrality and Baryon Number Density

$\mu_b = m_b + k_{Fb}^2/2m_b + \mathbf{U_b\ (k_{Fb})}$ for baryons (non-rela. approx.)

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

Equilibrium Conditions:

$$\mu_p = \mu_{\Sigma+} = \mu_n - \mu_e$$

$$\mu_\Lambda = \mu_{\Sigma 0} = \mu_{\Xi 0} = \mu_n$$

$$\mu_{\Sigma-} = \mu_{\Xi-} = \mu_n + \mu_e$$

$$\mu_\mu = \mu_e$$

10 k_F are determined by 10 conditions

Charge neutrality condition:

$$k_{Fp}^3 + k_{F\Sigma+}^3 = k_{F\Sigma-}^3 + k_{F\Xi-}^3 + k_{Fe}^3 + k_{F\mu}^3$$

Baryon Number Density:

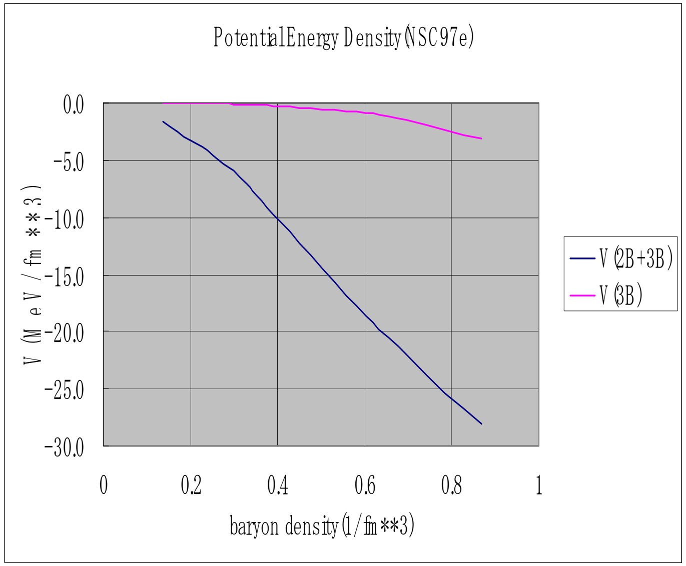
$$\rho_b = (k_{Fp}^3 + k_{Fn}^3 + +k_{F\Lambda}^3 + k_{F\Sigma-}^3 + k_{F\Sigma 0}^3 + k_{F\Sigma+}^3 + k_{F\Xi-}^3 + k_{F\Xi 0}^3)/3\pi^2$$

Potential Energy Densities in equilibrated baryonic matter

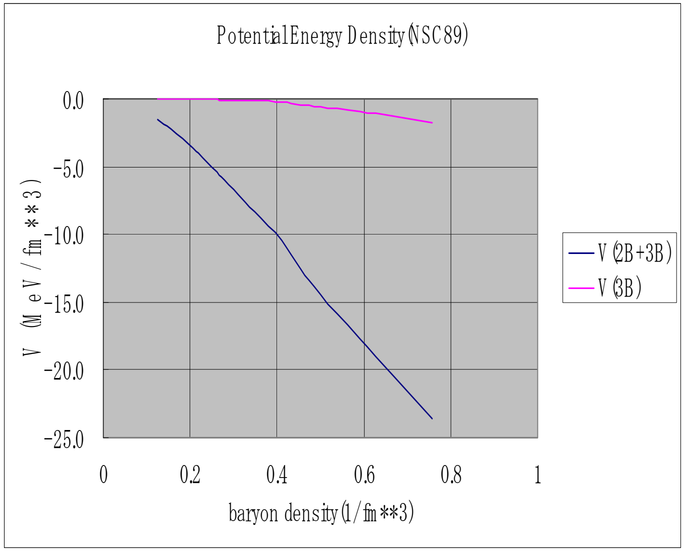
V(2BF+3BF) in MeV/fm^3

NN,YN,YY interactions:

NSC97e



NSC89



-30MeV/fm^3 at around 5ρ_0