Quarks and Compact Stars（KIAA at Peking University, Beijing, Oct. 20-22, 2014)

Coexistence of kaon condensation and hyperons in hadronic matter and its relevance to quark matter

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1. Introduction

Multi-strangeness system in hadronic matter

In neutron-stars

Kaon condensation

hyperonic matter
(Λ, Σ, Ξ, ・・・
in the ground state)

Strange matter
(u, d, s quark matter)

・Softening of EOS

・Rapid cooling of neutron stars

・Coexistence of antikaons and hyperons

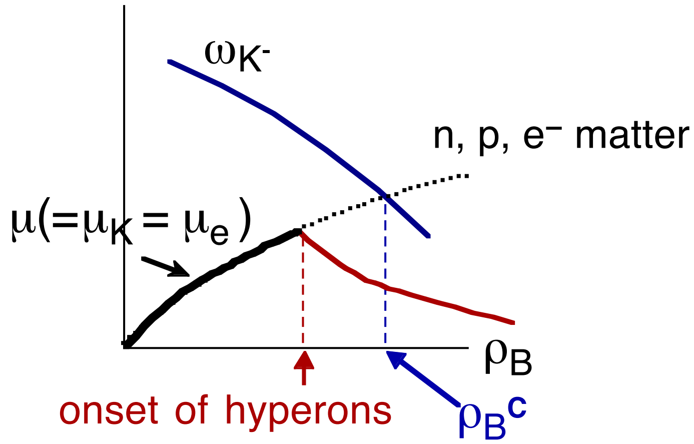
(Relativistic Mean-Field theory)

[P.J.Ellis, R.Knorren and M.Prakash, Phys. Rev. C52(1995), 3470.
J. Schaffner and I.N.Mishustin, Phys. Rev. C53(1996), 1416.]

・Possible appearance of kaons from hyperon matter depends on kaon-baryon interactions

(possibility of third family)

[S. Banik and D. Bandyopadhyay,
Phys. Rev. C 63 (2001) 035802; C64 (2001) 055805.]



(Quark Meson Coupling models)

[D. P. Menezes, P. K. Panda, C. Providencia, Phys. Rev. C 72 (2005) 035802.]

[C. Y. Ryu, C. H. Hyun, S. W. Hong, and B. T. Kim, Phys. Rev. C 75 (2007), 055804.]

(effect of δ meson)

[G.Y.Shao, Y.X.Liu, Phys. Rev. C82, 055801(2010).]

(effective chiral Lagrangian + phenomenological Baryon-Baryon int.

[T. Muto, Nucl. Phys. A754 (2005) 350; Phys. Rev. C77, 015810 (2008).]

・Most of the models including coexistent phase of Kaon condensation and hyperons predict $M_{max} < 2 M_{\odot}$

↕

Observations

$M(\text{PSR J1614-2230}) = 1.97 \pm 0.04 M_{\odot}$

[P. Demorest, T.Pennucci, S. Ransom, M. Roberts and J.W.T.Hessels, Nature 467 (2010) 1081.]

$M(\text{PSR J0348+0432}) = (2.01 \pm 0.04) M_{\odot}$

[J. Antoniadis et al., Science 340, 6131 (2013).]

How to reconcile theories with observations ?

We consider

coexistence of kaon condensation with hyperonic matter in neutron stars

based on the RMF model coupled with nonlinear effective chiral Lagrangian,

which is the same interaction model as used in studying

multi-antikaonic nuclear bound states with hyperon-mixing for finite nuclei

[T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]

[T. Muto, T. Maruyama and T. Tatsumi, Genshikaku Kenkyu 57 Supplement 3, 230(2013).]

⇒ Repulsive effects to make the EOS stiff at high densities

- Baryon potentials composed from kaon-baryon interactions and baryon-baryon interactions
- Consistency with observation of massive neutron stars

2. Outline of the model

2-1. Baryon-Baryon interaction

Baryons: $(p, n, \Lambda, \Sigma^-, \Xi^-)$

Mesons: $\sigma, \omega, \rho, \sigma^*, \phi$

Relativistic mean-field theory

$$\begin{aligned}\mathcal{L}_{B,M} &= \sum_B \overline{B}(i\gamma^\mu D_\mu - m_B^*)B + \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) - U(\sigma) + \frac{1}{2}(\partial^\mu\sigma^*\partial_\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2}) \\ &- \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}R^{\mu\nu}R_{\mu\nu} + \frac{1}{2}m_\rho^2 R^\mu R_\mu - \frac{1}{4}\phi^{\mu\nu}\phi_{\mu\nu} + \frac{1}{2}m_\phi^2\phi^\mu\phi_\mu \\ &- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} ,\end{aligned}$$

$$m_B^*(r) = m_B - g_{\sigma B}\sigma(r) - g_{\sigma^* B}\sigma^*(r)$$

parameters

$$D^\mu \equiv \partial^\mu + ig_{\omega B}\omega^\mu + ig_{\rho B}\vec{\tau}\cdot\vec{R}^\mu + ig_{\phi B}\phi^\mu + iQA^\mu$$

--- NN interaction --- gross features of normal nuclei and nuclear matter

- saturation properties of nuclear matter (ρ_0 =0.153 fm^{-3})
- binding energy of nuclei and proton-mixing ratio
- density distributions of p and n

→ $g_{\sigma N}$, $g_{\omega N}$, $g_{\rho N}$

--- vector meson couplings for Y --- SU(6) symmetry

$$g_{\omega\Lambda} = g_{\omega\Sigma^-} = 2g_{\omega\Xi^-} = \frac{2}{3}g_{\omega N} \qquad g_{\phi\Lambda} = g_{\phi\Sigma^-} = \frac{1}{2}g_{\phi\Xi^-} = -\frac{\sqrt{2}}{3}g_{\omega N}$$

$$g_{\rho\Lambda} = 0 \qquad g_{\rho\Sigma^-} = 2g_{\rho\Xi^-} = 2g_{\rho N}$$

--- scalar meson couplings for Y ---

Hyperon potentials deduced from hypernuclear experiments

(analysis of Λ single-particle orbitals)

$$U_{\Lambda}^{N}(\rho_0) = -g_{\sigma\Lambda}\sigma + g_{\omega\Lambda}\omega_0 = -27\ \mathrm{MeV}$$ → $g_{\sigma\Lambda} = 3.84$

- $(K^-, \pi^{\pm})$ at BNL → T=3/2 state: strongly repulsive

[J. Dabrowski, Phys. Rev. C60 (1999), 025205.] $V_{\Sigma^-}(k_\Sigma) = V_0(k_\Sigma) - \frac{1}{2}V_1(k_\Sigma)\cdot\frac{Z-N}{A}$

23.5 MeV 80.4 MeV

- (π^-, K^+) at KEK

[H. Noumi et al., , Phys. Rev. Lett. 89 (2002), 072301; ibid 90(2003), 049902(E).]

- analysis of Σ^- atoms : repulsive [C. J. Batty, E. Friedman, A. Gal, Phys. Rep. 287 (1997), 385.]

$$U_{\Sigma^-}^{N}(\rho_0) = -g_{\sigma\Sigma^-}\sigma + g_{\omega\Sigma^-}\omega_0 = 23.5\ \mathrm{MeV}$$ repulsive case → $g_{\sigma\Sigma^-} = 2.28$

$$U_{\Xi^-}^{N}(\rho_0) = -g_{\sigma\Xi^-}\sigma + g_{\omega\Xi^-}\omega_0 = -16\ \mathrm{MeV}$$ → $g_{\sigma\Xi^-} = 2.0$

[T. Fukuda et al., Phys. Rev. C58 (1998), 1306. , P. Khaustov et al., Phys. Rev. C61 (2000), 054603.]

$$g_{\sigma^* N} = g_{\sigma^*\Lambda} = g_{\sigma^*\Sigma^-} = g_{\sigma^*\Xi^-} = 0$$

2-2 $\bar{K}-B, \bar{K}-\bar{K}$ interactions

$SU(3)_L \times SU(3)_R$ chiral effective Lagrangian

[D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175 (1986) 57.]

$$\mathcal{L} = \frac{1}{4} f^2 \mathrm{Tr}\, \partial^\mu \Sigma^\dagger \partial_\mu \Sigma + \frac{1}{2} f^2 \Lambda_{\chi SB} (\mathrm{Tr}\, M(\Sigma - 1) + \mathrm{h.c.})$$
$$+ \mathrm{Tr}\, \bar{\Psi}(i\partial\!\!\!/ - m_B)\Psi + \mathrm{Tr}\, \bar{\Psi} i\gamma^\mu [V_\mu, \Psi] + D\mathrm{Tr}\, \bar{\Psi}\gamma^\mu\gamma^5 \{A_\mu, \Psi\}$$
$$+ F\mathrm{Tr}\, \bar{\Psi}\gamma^\mu\gamma^5 [A_\mu, \Psi] + a_1 \mathrm{Tr}\, \bar{\Psi}(\xi M^\dagger \xi + \mathrm{h.c.})\Psi$$
$$+ a_2 \mathrm{Tr}\, \bar{\Psi}\Psi(\xi M^\dagger \xi + \mathrm{h.c.}) + a_3 (\mathrm{Tr}\, M\Sigma + \mathrm{h.c.}) \mathrm{Tr}\, \bar{\Psi}\Psi ,$$

Baryons

$\Psi \Rightarrow$ (p, n, Λ, Ξ^-, Σ^-)

$$M = \mathrm{diag}(m_u, m_d, m_u)$$

Meson fields ($K^\pm$) $\quad \Sigma \equiv e^{2i\Pi/f}$

Vector current $\quad V^\mu = \frac{1}{2}(\xi^\dagger \partial^\mu \xi + \xi \partial^\mu \xi^\dagger)$

$$\Pi = \pi_a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & K^+ \\ 0 & 0 & 0 \\ K^- & 0 & 0 \end{pmatrix}$$

Axial-vector current $\quad A^\mu = \frac{i}{2}(\xi^\dagger \partial^\mu \xi - \xi \partial^\mu \xi^\dagger)$

$(\xi \equiv \Sigma^{1/2} = e^{i\pi_a T_a/f})$

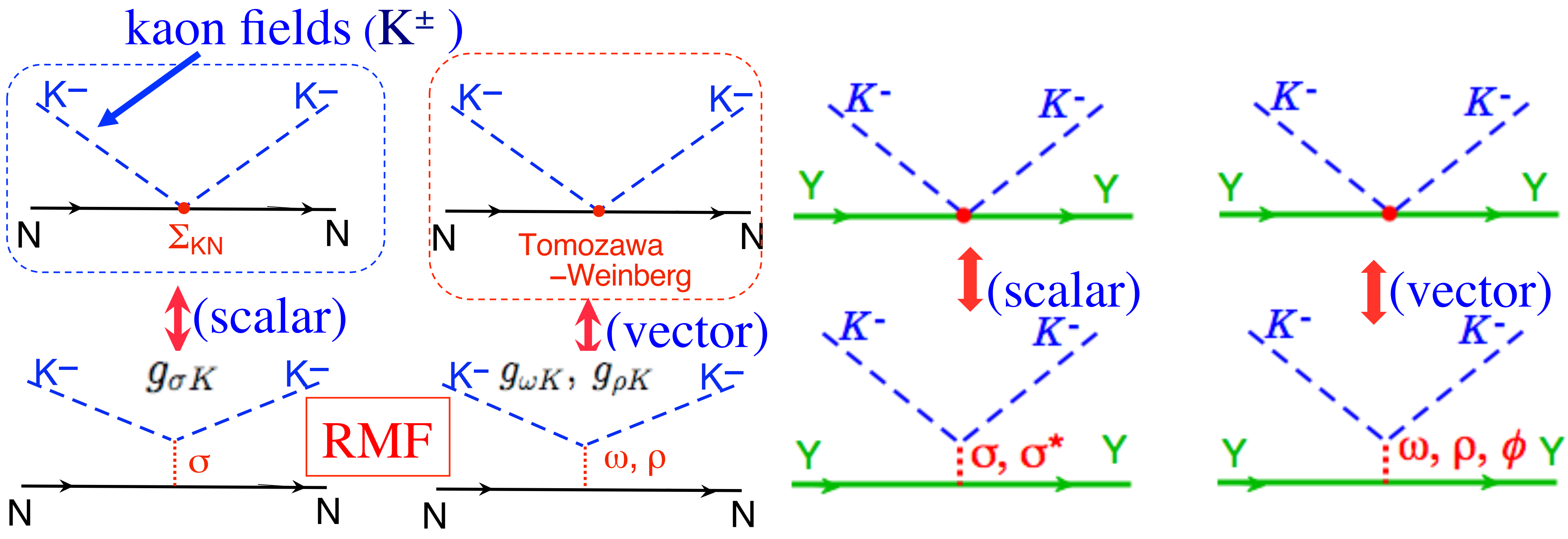
Classical K^- field

$$K^\pm = \frac{f}{\sqrt{2}} \theta \exp(\pm i \mu_K t)$$

Meson decay constant

$f = 93$ MeV

μ_K : kaon chemical potential



Kaonic part of the Lagrangian density

$$\mathcal{L}_{KB} = \frac{1}{2}\left\{1+\left(\frac{\sin\theta}{\theta}\right)^2\right\}\partial^\mu K^+\partial_\mu K^- + \frac{1-\left(\frac{\sin\theta}{\theta}\right)^2}{2f^2\theta^2}\left\{(K^+\partial_\mu K^-)^2+(K^-\partial_\mu K^+)^2\right\}$$

$$-\left\{m_K^2-2m_K(g_{\sigma K}\sigma+g_{\sigma^* K}\sigma^*)\right\}\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2 K^+K^-$$

S wave scalar int.

$$+\ i(g_{\omega K}\omega_0+g_{\rho K}R_0+g_{\phi K}\phi_0)\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2(K^+\partial_\mu K^- - \partial_\mu K^+ K^-)$$

S wave vector int.

parameters

--- vector meson couplings for Kaon ---

Corresponding to
the Tomozawa-Weinberg term

$$X_0 \equiv g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0 \sim \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega N} + \frac{g_{\rho K}}{m_\rho^2}g_{\rho N}\right) = 1 \quad \text{for } p$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega N} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho N}\right) = \frac{1}{2} \quad \text{for } n$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Lambda} + \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Lambda} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Lambda}\right) = 0 \quad \text{for } \Lambda$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Sigma^-} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Sigma^-} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Sigma^-}\right) = -\frac{1}{2} \quad \text{for } \Sigma^-$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Xi^-} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Xi^-} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Xi^-}\right) = -1 \quad \text{for } \Xi^-$$

$$g_{\omega K} = 3.05$$
$$g_{\rho K} = 2.00$$
$$g_{\phi K} = 7.33$$

quark – isospin counting rule
SU(6) symmetry

$$g_{\omega K} = g_{\omega N}/3 = 2.90$$
$$g_{\rho K} = g_{\rho N} = 4.26$$
$$g_{\phi K} = 6.04/\sqrt{2}$$

--- scalar meson couplings for Kaon ---

$g_{\sigma^* K} = 2.65/2$: Decay of $f_0(975)$

K^- optical potential depth :

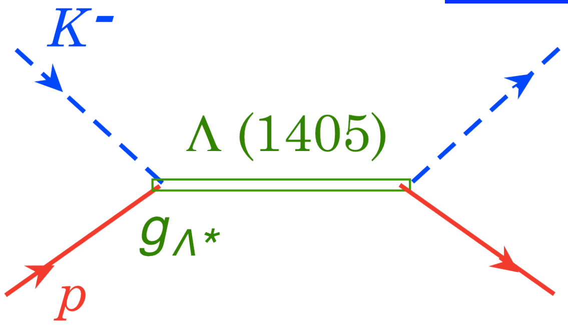
$U_K = -(g_{\sigma K}\sigma + g_{\omega K}\omega_0)$ at ρ_0

→ $g_{\sigma K}$

$U_K = (-180, -120, -80)$ MeV

(extremely, moderately, weakly) attractive

Effect of Λ(1405) and range terms



$$+ \; O(\mu^2)$$

$$d_p = (d_1 + d_2)/(2f^2) = d_{\Xi^-}$$

$$d_n = d_1/(2f^2) = d_{\Sigma^-}$$

$$d_\Lambda = (d_1 + 5d_2/6)/(2f^2)$$

Energy correction

$$\Delta\epsilon = -\frac{1}{2}(f\mu\sin\theta)^2\left[\rho_p^s\left\{d_p + \frac{g_{\Lambda^*}^2}{2f^2}\frac{m_{\Lambda^*} - m_N - \mu}{(m_{\Lambda^*} - m_N - \mu)^2 + \gamma_{\Lambda^*}^2}\right\} + d_n\rho_n^s + d_\Lambda\rho_\Lambda^s + d_{\Sigma^-}\rho_{\Sigma^-}^s + d_{\Xi^-}\rho_{\Xi^-}^s\right]$$

→ Effective baryon masses

On-shell S-wave KN scattering lengths

$$a(K^-p) = \frac{1}{4\pi f^2(1 + m_K/m_N)}\left(\Sigma_{KN} + m_K + d_p f^2 m_K^2 + \frac{g_{\Lambda^*}^2}{2}\frac{m_K^2}{m_{\Lambda^*} - m_N - m_K - i\gamma_{\Lambda^*}}\right)$$

$$= (-0.67 + i0.64)\ \text{fm}$$

KN sigma term ⟷ $\Sigma_{KN} = \dfrac{2m_K f^2 g_{\sigma K} g_{\sigma N}}{m_\sigma^2}$

$$a(K^- n) = \frac{1}{4\pi f^2(1+m_K/m_N)}\left(\Sigma_{KN} + \frac{1}{2}m_K + d_n f^2 m_K^2\right)$$

$$= (0.37 + i0.60)\ \text{fm}$$

$$a(K^+ p) = \frac{1}{4\pi f^2(1+m_K/m_N)}\left(\Sigma_{KN} - m_K + d_p f^2 m_K^2 + \frac{g_{\Lambda^*}^2}{2}\frac{m_K^2}{m_{\Lambda^*} - m_N + m_K - i\gamma_{\Lambda^*}}\right)$$

$$= -0.33\ \text{fm}$$

$$a(K^+ n) = \frac{1}{4\pi f^2(1+m_K/m_N)}\left(\Sigma_{KN} - \frac{1}{2}m_K + d_n f^2 m_K^2\right)$$

$$= -0.16\ \text{fm}$$

$$d_p = (0.351 - \Sigma_{KN}/m_K)/(f^2 m_K)$$

$$d_n = (0.130 - \Sigma_{KN}/m_K)/(f^2 m_K)$$

$$g_{\Lambda^*} = 0.583 \quad \gamma_{\Lambda^*} = 12.4\ \text{MeV}$$

2-3. Thermodynamic potential

$$\Omega = \int d^3r \mathcal{H}(r) + \mu_Q \hat{Q} + \nu \hat{N}_{\rm B}$$

- charge neutrality
- baryon number conservation

$\delta\Omega = 0$ as $\rho_a \to \rho_a + \delta\rho_a$

$(a = K^-, p, n, \Lambda, \Sigma^-, \Xi^-)$

$$\mu_a = \frac{\partial \mathcal{E}}{\partial \rho_a}$$

$$\mu_K = \mu_e = \mu_Q$$

$$\mu_p = -(\mu_Q + \nu)$$

$$\mu_n = \mu_\Lambda = -\nu$$

$$\mu_{\Xi^-} = \mu_{\Sigma^-} = \mu_Q - \nu$$

Chemical equilibrium for weak processes

$$\mu_K = \mu_e$$

$$\mu_n = \mu_p + \mu_e$$

$$\mu_n = \mu_\Lambda$$

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

$$\mu_\Lambda + \mu_e = \mu_{\Xi^-}$$

Onset condition of kaon condensation (assumed continuous phase transition)

Lowest K^- energy : $\omega_{K^-} = \mu_{K^-} = \mu_e (= \mu_Q)$

Equations of motion for meson fields

Scalar mean fields

$$m_\sigma^2\sigma = -\frac{dU}{d\sigma} + g_{\sigma N}(\rho_n^s + \rho_p^s) + g_{\sigma\Lambda}\rho_\Lambda^s + g_{\sigma\Sigma^-}\rho_{\Sigma^-}^s + 2f^2 g_{\sigma K} m_K(1 - \cos\theta)$$

$$m_\sigma^2\sigma^* = g_{\sigma^*\Lambda}\rho_\Lambda^s + g_{\sigma^*\Sigma^-}\rho_{\Sigma^-}^s + 2f^2 g_{\sigma^* K} m_K(1 - \cos\theta)$$

Vector mean fields

$$m_\omega^2\omega_0 = g_{\omega N}(\rho_n + \rho_p) + g_{\omega\Lambda}\rho_\Lambda + g_{\omega\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\omega K}\mu_K(1 - \cos\theta)$$

$$m_\rho^2 R_0 = g_{\rho N}(\rho_p - \rho_n) + g_{\rho\Lambda}\rho_\Lambda - g_{\rho\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\rho K}\mu_K(1 - \cos\theta)$$

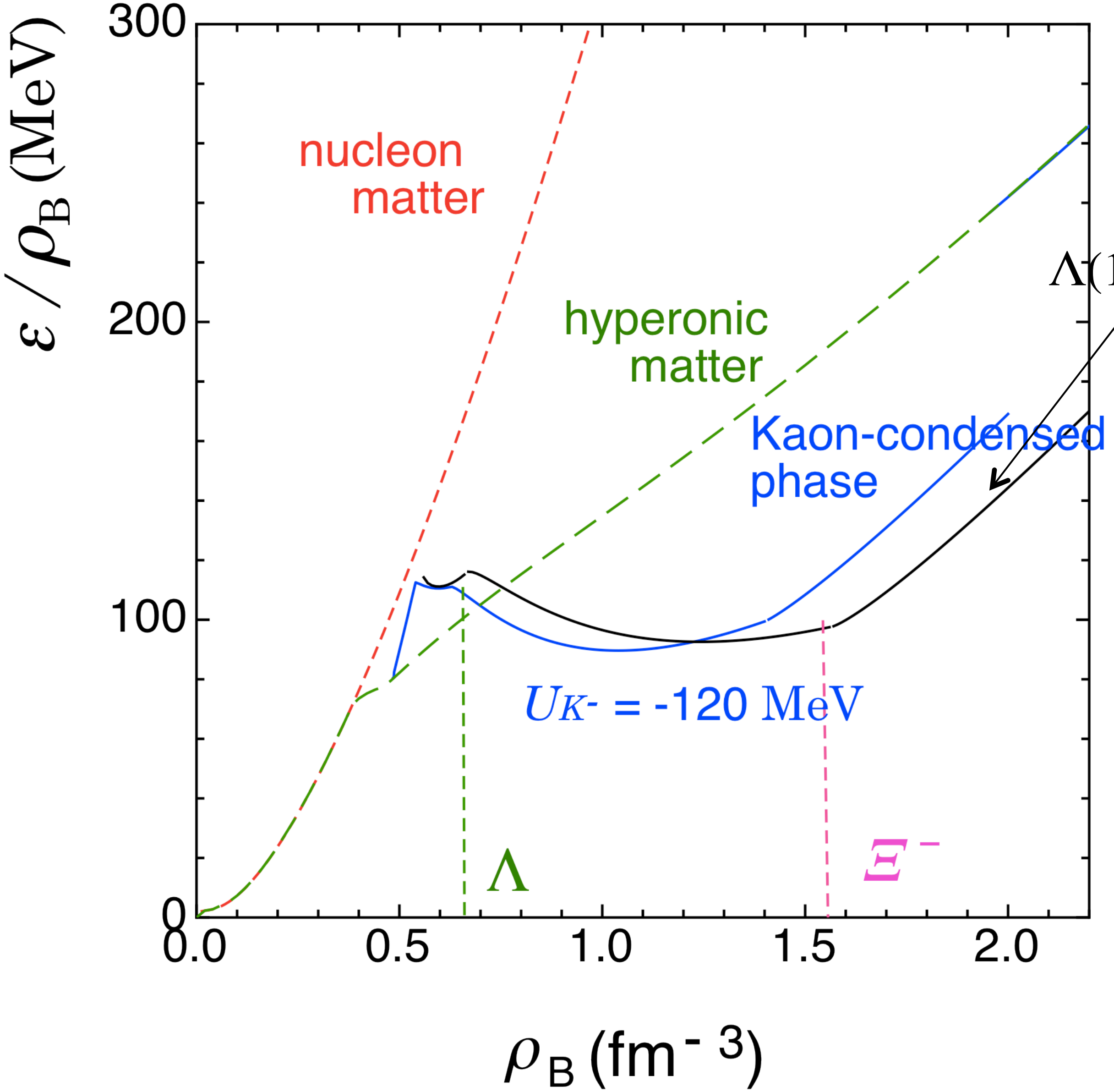
$$m_\phi^2\phi_0 = g_{\phi\Lambda}\rho_\Lambda + g_{\phi\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\phi K}\mu_K(1 - \cos\theta)$$

3. Numerical results

3. Results

3-1. EOS in β-equilibrated matter

Energy per particle



chemical equilibrium for weak processes

$n \rightleftharpoons p\ K^-$

$n \rightleftharpoons p\ e^-\ (\bar{\nu}_e)$

$p\ e^- \rightleftharpoons \Lambda\ (\nu_e)$

$n\ e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

$\Lambda\ e^- \rightleftharpoons \Xi^-\ (\nu_e)$

$\overline{K}$- Baryon interactions in K$^-$ field equation

$\delta\Omega/\delta\theta(r) = 0$ K$^-$ field equation

$$m_K^2 - 2g_{\sigma K} m_K \sigma - 2g_{\sigma^* K} m_K \sigma^* - 2\mu_K (g_{\omega K}\omega_0 + g_{\rho K} R_0 + g_{\phi K}\phi_0) - \mu_K^2 \cos\theta = 0$$

S-wave scalar int.

$$m_K^{*2} \equiv m_K^2 - 2g_{\sigma K} m_K \sigma - 2g_{\sigma^* K} m_K \sigma^*$$

$$(\ U_{K^-} = -g_{\sigma K}\sigma - g_{\omega K}\omega_0 \ )$$

S-wave vector int.

$$X_0 \equiv g_{\omega K}\omega_0 + g_{\rho K} R_0 + g_{\phi K}\phi_0$$

Chiral symmetry

S-wave vector int.

$$
\begin{aligned}
\mu X_0 &= \mu(g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0) \\
&= \frac{\mu}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right) \\
&- 2\left[\left(\frac{g_{\omega K}}{m_\omega}\right)^2 + \left(\frac{g_{\rho K}}{m_\rho}\right)^2 + \left(\frac{g_{\phi K}}{m_\phi}\right)^2\right](\mu f)^2(1-\cos\theta)
\end{aligned}
$$

Equations of motion for vector mean fields

$$m_\omega^2\omega_0 = g_{\omega N}(\rho_n + \rho_p) + g_{\omega\Lambda}\rho_\Lambda + g_{\omega\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\omega K}\mu_K(1-\cos\theta)$$

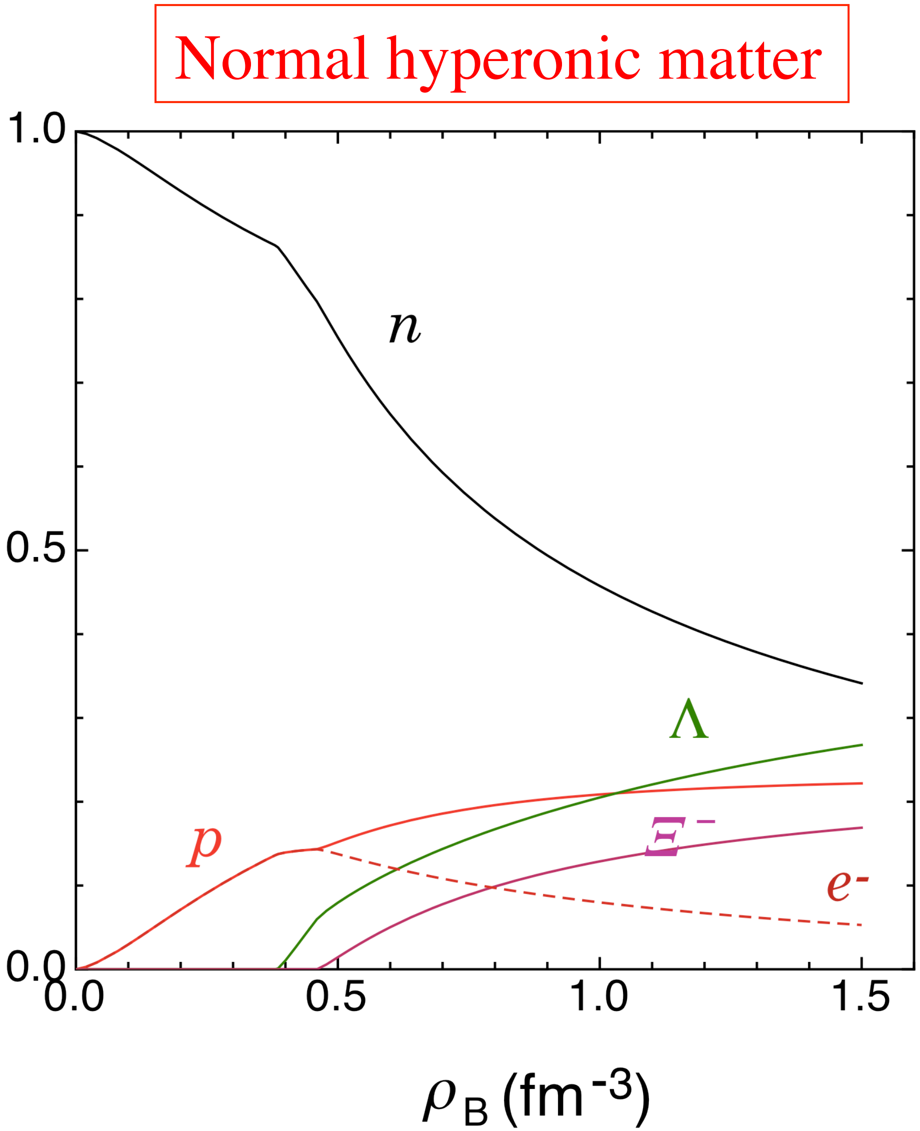
$$m_\rho^2 R_0 = g_{\rho N}(\rho_p - \rho_n) + g_{\rho\Lambda}\rho_\Lambda - g_{\rho\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\rho K}\mu_K(1-\cos\theta)$$

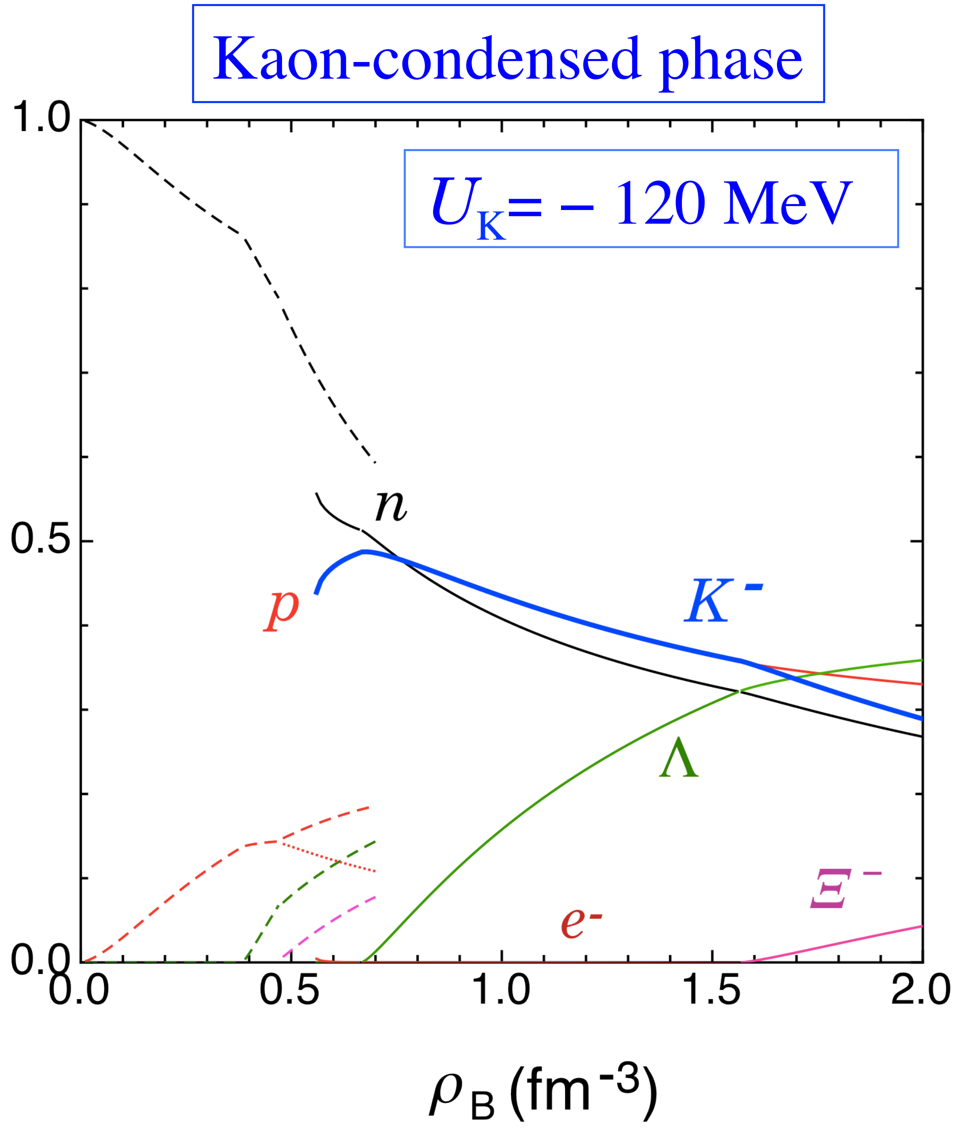
$$m_\phi^2\phi_0 = g_{\phi\Lambda}\rho_\Lambda + g_{\phi\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\phi K}\mu_K(1-\cos\theta)$$

Vector interaction between K^- mesons and hyperons (Σ^- and Ξ^-) works repulsively as far as $\mu > 0$, unfavorable for coexistence.

Development of kaon condensates suppresses vector attraction

3-2. Particle fractions





Problems: Too soft EOS resulting from coexistence of kaon condensates and hyperons

K^- -baryon attractive interactions, especially, the S-wave scalar attractions lead to additional softening of the EOS as compared with the case of hyperonic matter.

The soft EOS cannot give massive compact stars ($\sim 2\ M_\odot$).

Strong repulsion between baryons and suppression of attractive $\bar{K}$ - B interaction at high densities are needed.

4. Discussion and summary

Repulsive effects on EOS

(1) Kaon-Baryon sector -- suppression of K^- - B attractions ---

(i) K^- potential depth $U_K \sim -87$ MeV → $\rho_B^C \sim 12\ \rho_0$

($\langle N | \bar{s}s | N \rangle \sim 0$, $\Sigma_{KN} \sim 280$ MeV)

$U_K = -120$ MeV → $\rho_B^C \sim 4.5\ \rho_0$

(ii) S-wave K^- - B vector int.

Consequence from chiral symmetry

Vector interaction between K^- mesons and hyperons (Σ^- and Ξ^-) works repulsively as far as $\mu > 0$, leading to suppression of kaon condensates

Development of kaon condensates suppresses vector attraction

But, such suppression of K^- - baryon attractions is not enough for making the EOS stiffer.

Strong repulsion between baryons at high densities are needed.

(Recent Lattie QCD) $\bar{s}s$ content in the nucleon is small.

[R. D. Young, A. W. Thomas, Nucl. Phys. A844(2010) 266c.]

$$\Sigma_{KN} = \frac{1}{2}(m_u + m_s)\langle N|\bar{u}u + \bar{s}s|N\rangle$$
$$\simeq \frac{1}{2}\left(1 + \frac{m_s}{m_u}\right)\left(\frac{\Sigma_{\pi N}}{1 + m_d/m_u} + \frac{m_u}{m_s}\sigma_s\right)$$

$$\sigma_s = m_s\langle N|\bar{s}s|N\rangle$$
~ 0

$$\Sigma_{\pi N} = m_l\langle N|\bar{u}u + \bar{d}d|N\rangle \quad m_l = \frac{1}{2}(m_u + m_d)$$

In case $\Sigma_{\pi N} = 64 \pm 7$ MeV [M.M.Pavan et al., PiN Newslett. 16, 110(2002).]

→ Scalar int.: $\Sigma_{KN} \sim 280$ MeV for $m_s/m_l = 25$, $m_d/m_u = 2$

($U_K \sim -80$MeV)

↕

- In flight (K^-, N) KEK, BNL

deep K-nucleus potential, $U_K \sim -200$ MeV
(analysis of missing mass spectra)

[T. Kishimoto et al., Prog. Theor. Phys. 118 (2007), 181.]

Making EOS stiffer at high density

(2) Baryon-baryon sector

(i) Phenomenological universal YNN, YYN, YYY repulsions

[S. Nishizaki, Y. Yamamotoand T. Takatsuka,
Prog. Theor.Phys. 108 (2002) 703.])

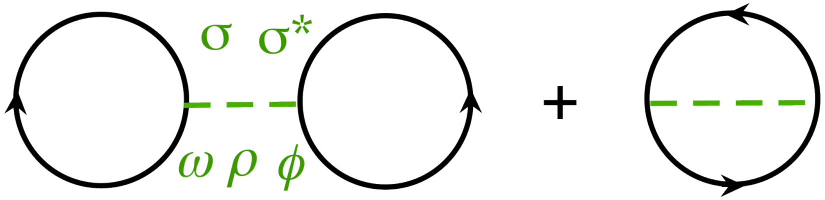
(cf : RMF extended to BMM, MMM type diagrams)

[K. Tsubakihara and A. Ohnishi, arXiv:1211.7208.]

(ii) relativistic Hartree-Fock

Introduction of tensor coupling of vector mesons

Cf. for hyperonic matter,
[T. Miyatsu, T. Katayama, K. Saito, Phys. Lett.B709 242(2012).]



Connection to quark matter

(3) Relation between kaon condensation in hadronic matter and that in quark matter

Hadron phase and quark phase are connected with cross-over region

→ Massive stars ($\sim 2\, M_\odot$)

[K. Masuda, T. Hatsuda, T. Takatsuka, Astrophys. J. Lett. 764, 12 (2013).]

Coexistence of kaon-condensates and hyperons for hadronic phase → Strange quark matter (kaon-condensates in quark matter)