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Possible coexistence of kaon condensation and hyperons in multi-strangeness systems

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1. Introduction

1-1 Multi-strangeness system in hadronic matter

In neutron-stars

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

Kaon condensation

Bose-Einstein condensation of kaons (K^-)

Strange matter (u, d, s quark matter)

- Softening of EOS
- Rapid cooling of neutron stars
- Coexistence of antikaons and hyperons

Toward unified description based on the same Kaon-baryon(B), B-B interaction model.

In nuclei

Kaonic nuclei [Y.Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.]

Multi-Antikaonic Nuclei

relativistic mean-field theory (RMF) [T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]

- Coexistence of antikaons and hyperons

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

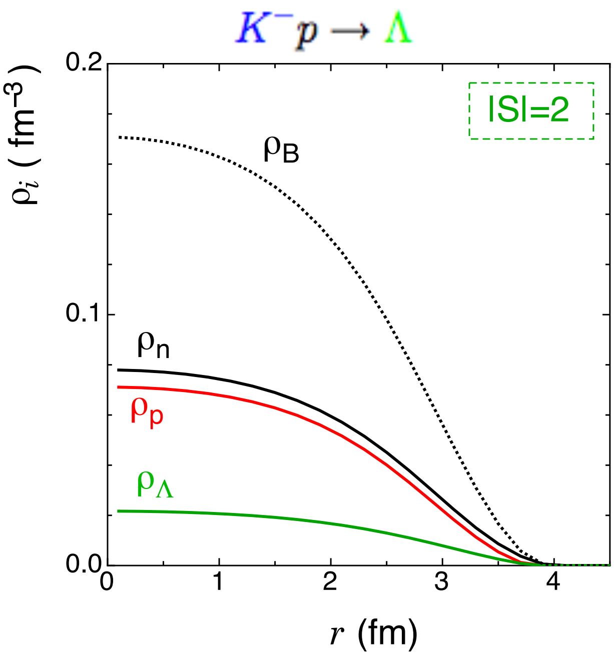
Finite nuclei

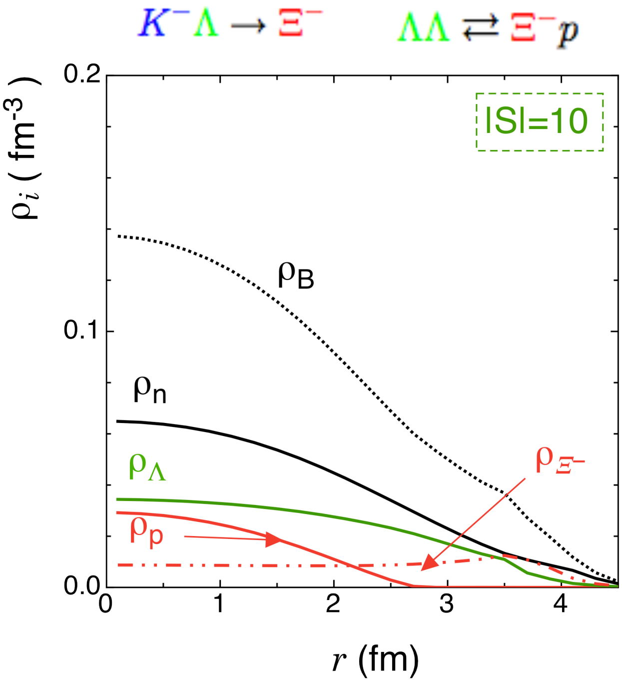
A=15, Z=8 ($^{15}_{8}O$)

| U_K | < 180 MeV

Ground state : Multi-hypernuclei

No K^- meson is bound.





Central density $\rho_B^{(0)} \sim \rho_0$

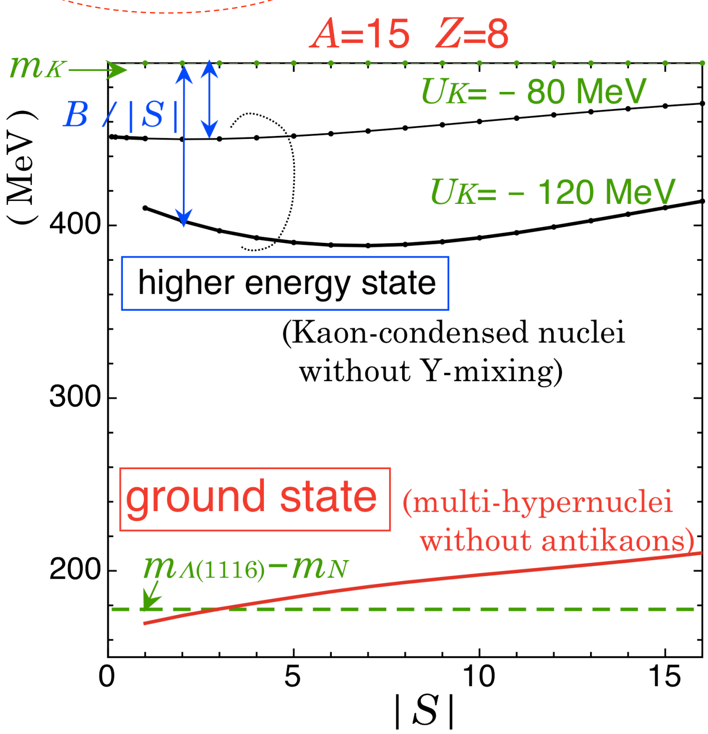
Finite nuclei

Energy difference per unit of strangeness from normal nuclei (|S| = 0)

Total energy

$$\left[E(A,Z,|S|) - E(A,Z,0)\right]/|S|$$

| U_K | < 180 MeV



For |S| >3

Strong decay of multi-hypernuclei to $\Lambda(1116) + N$

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 for

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

[T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009). Genshikaku Kenkyu 57 Supplement 3, 230(2013).]

Consistency with observation of massive neutron stars

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

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

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

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

2. Outline of the model

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

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

2-1. Baryon-Baryon interaction

Relativistic mean-field theory

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

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

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

parameters

--- 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)

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

- $(K^-, \pi^\pm)$ 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.]

$$U_{\Sigma^-}^N(\rho_0) = -g_{\sigma\Sigma^-}\sigma + g_{\omega\Sigma^-}\omega_0 = 23.5 \text{ MeV}$$

repulsive case → $g_{\sigma\Sigma^-} = 2.28$

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

[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.]

$$\mathcal{L} = \frac{1}{4}f^2\mathrm{Tr}\,\partial^\mu\Sigma^\dagger\partial_\mu\Sigma + \frac{1}{2}f^2\Lambda_{\chi SB}(\mathrm{Tr}\,M(\Sigma-1)+\mathrm{h.c.})$$
$$+\mathrm{Tr}\,\bar{\Psi}(i\not{\partial}-m_B)\Psi + \mathrm{Tr}\,\bar{\Psi}i\gamma^\mu[V_\mu, \Psi] + D\,\mathrm{Tr}\,\bar{\Psi}\gamma^\mu\gamma^5\{A_\mu, \Psi\}$$
$$+F\,\mathrm{Tr}\,\bar{\Psi}\gamma^\mu\gamma^5[A_\mu, \Psi] + a_1\mathrm{Tr}\,\bar{\Psi}(\xi M^\dagger\xi + \mathrm{h.c.})\Psi$$
$$+a_2\mathrm{Tr}\,\bar{\Psi}\Psi(\xi M^\dagger\xi + \mathrm{h.c.}) + a_3(\mathrm{Tr}\,M\Sigma + \mathrm{h.c.})\mathrm{Tr}\,\bar{\Psi}\Psi\,,$$

Baryons

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

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

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

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

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

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

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

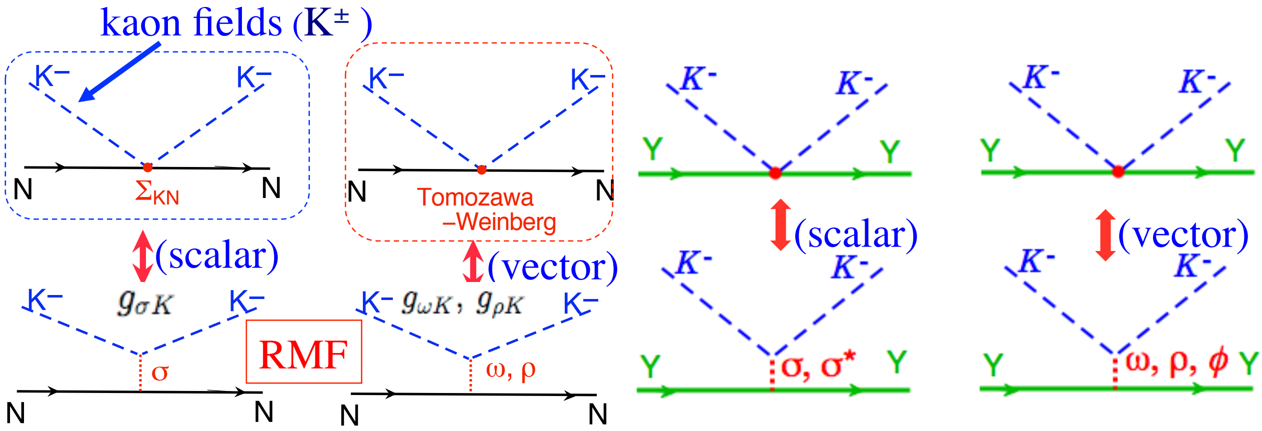
Classical K^- field

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

Meson decay constant

f =93 MeV

μ_K : kaon chemical potential



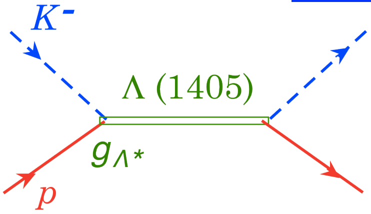
Kaonic part of the Lagrangian density

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

$$- \underbrace{\left\{m_K^2 - 2m_K(g_{\sigma K}\sigma + g_{\sigma^* K}\sigma^*)\right\}}_{\text{S wave scalar int.}}\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2 K^+K^-$$

$$+ \underbrace{i(g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0)}_{\text{S wave vector int.}}\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2 (K^+\partial_\mu K^- - \partial_\mu K^+ K^-)$$

Effect of Λ(1405) and range terms



$+ \ O(\mu^2)$

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

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

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

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

determined to reproduce
the on-shell S-wave KN scattering lengths

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

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

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

parameters

--- vector meson couplings for Kaon ---

Corresponding to
the Tomozawa-Weinberg term

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

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

$$\Longleftrightarrow$$

$$g_{\omega K} = g_{\omega N}/3 = 2.90$$

$$g_{\rho K} = g_{\rho N} = 4.26$$

$$g_{\phi K} = 6.04/\sqrt{2}$$

c.f. quark – isospin counting rule
SU(6) symmetry

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

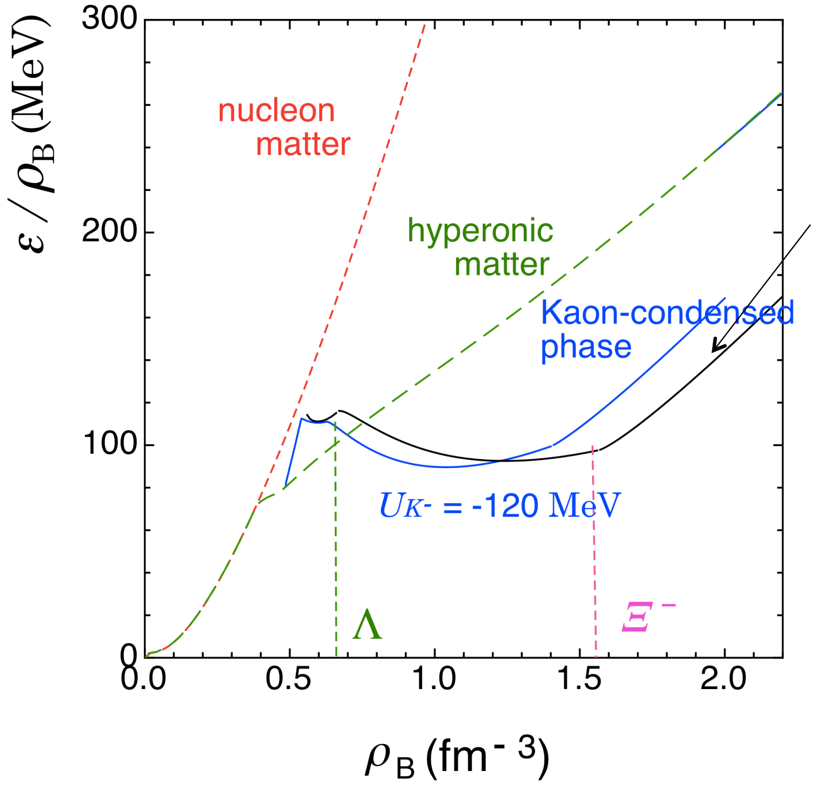
$\Rightarrow \boxed{g_{\sigma K}}$ (extremely, moderately, weakly) attractive

3. Numerical results

3. Results

3-1. EOS in β-equilibrated matter

Energy per particle



Including $\Lambda(1405)$ and range effect

chemical equilibrium for weak processes

$\boxed{n \rightleftharpoons p\ K^-}$

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

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

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

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

3-2. Comparison with multi-strangeness nuclei

Finite system formed in laboratory

Antikaons do not receive much $\bar{K}-B$ attraction ← Finite effects of nuclei

$\boxed{\omega_{K^-} > \mu_\Lambda - \mu_p}$

hard to satisfy

Chemical equilibrium for strong processes

$K^- p \rightleftharpoons \Lambda, \quad K^- \Lambda \rightleftharpoons \Xi^-, \quad K^- n \rightleftharpoons \Sigma^-$

In neutron stars

Antikaons receive much $\bar{K}-B$ attraction ← dense infinite matter

chemical equilibrium for weak processes

$\boxed{n \rightleftharpoons p\ K^-}$ $\quad p\ e^- \rightleftharpoons \Lambda\ (\nu_e) \quad n\ e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

$n \rightleftharpoons p\ e^-\ (\bar{\nu}_e) \quad \Lambda\ e^- \rightleftharpoons \Xi^-\ (\nu_e)$

K$^-$ chemical potential : $\boxed{\omega_{K^-} = \mu = \mu_n - \mu_p} = O(m_\pi) \rightarrow < 0$

for high densities

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 (~ 2 $M_\odot$).

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

Suppression mechanisms of K-Baryon attractions

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

$$m_K^2 - \underbrace{2g_{\sigma K} m_K \sigma - 2g_{\sigma^* K} m_K \sigma^*}_{\text{S-wave scalar int.}} - 2\mu_K \underbrace{(g_{\omega K}\omega_0 + g_{\rho K} R_0 + g_{\phi K}\phi_0)}_{\text{S-wave vector int.}} - \mu_K^2 \cos\theta = 0$$

S-wave scalar int.

--- Self-suppression of scalar int. ---

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

Scalar mean fields

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

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

Kaon condensation develops $\Rightarrow$ θ : large $\Rightarrow$ σ mean-field : large

Effective baryon mass : decrease

$$m_i^* = m_i - g_{\sigma i}\sigma - g_{\sigma^* i}\sigma^*$$

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

Baryon scalar density : decrease

$$\rho_i^s = \frac{2}{(2\pi)^3}\int d^3k \frac{m_i^*}{\sqrt{k^2 + m_i^{*2}}}$$

Saturation of σ mean-field

S-wave vector int.

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

Chiral symmetry

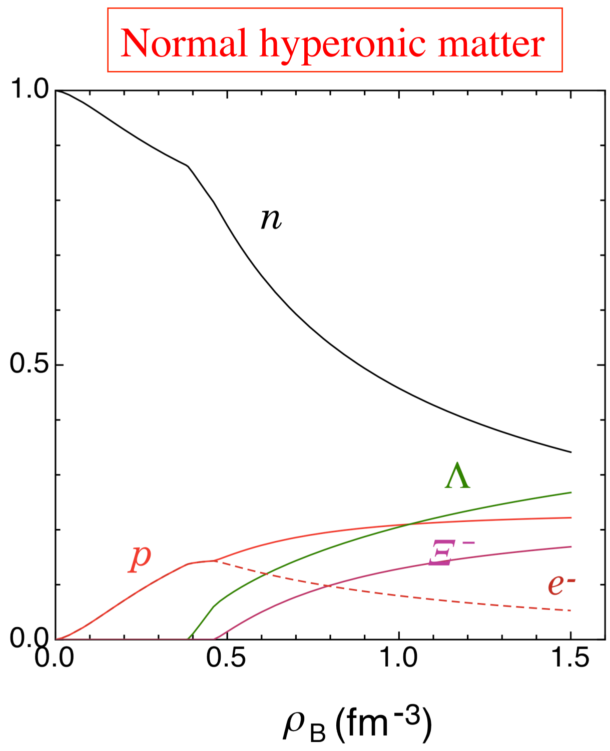
Equations of motion for vector mean fields

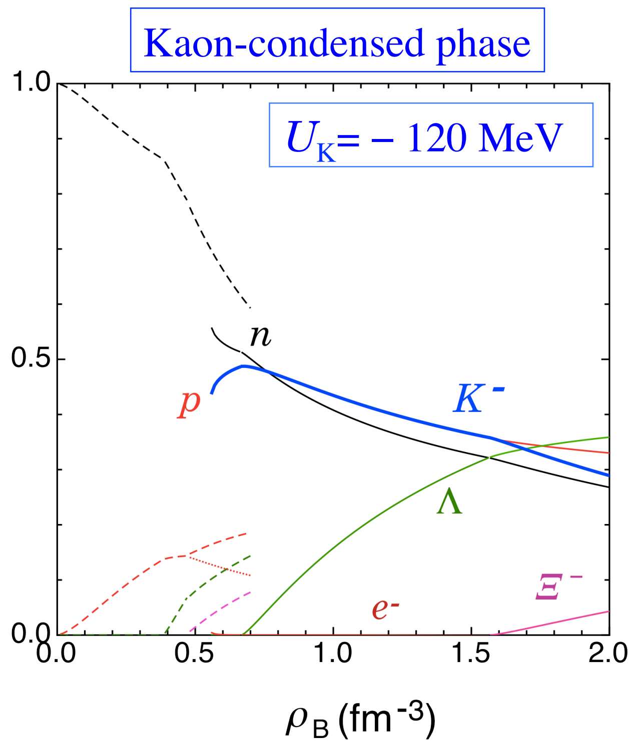
$$m_\omega^2\omega_0 = g_{\omega N}(\rho_n + \rho_p) + g_{\omega\Lambda}\rho_\Lambda + g_{\omega\Sigma^-}\rho_{\Sigma^-} + g_{\omega\Xi^-}\rho_{\Xi^-} - 2f^2 g_{\omega K}\mu_K(1-\cos\theta)$$
$$m_\rho^2 R_0 = g_{\rho N}(\rho_p - \rho_n) + g_{\rho\Lambda}\rho_\Lambda - g_{\rho\Sigma^-}\rho_{\Sigma^-} - g_{\rho\Xi^-}\rho_{\Xi^-} - 2f^2 g_{\rho K}\mu_K(1-\cos\theta)$$
$$m_\phi^2\phi_0 = g_{\phi\Lambda}\rho_\Lambda + g_{\phi\Sigma^-}\rho_{\Sigma^-} + g_{\phi\Xi^-}\rho_{\Xi^-} - 2f^2 g_{\phi K}\mu_K(1-\cos\theta)$$

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

3-3. Particle fractions





4. Discussion and summary

Repulsive effects on EOS

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

(i) K^- potential depth $\boxed{U_K \sim -87 \text{ MeV}}$ $\rightarrow$ $\rho_B^C \sim 12\ \rho_0$

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

$\boxed{U_K = -120 \text{ MeV}}$ $\rightarrow$ $\rho_B^C \sim 4.5\ \rho_0$

(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.

Making EOS stiffer at high density

(1) Baryon-baryon sector

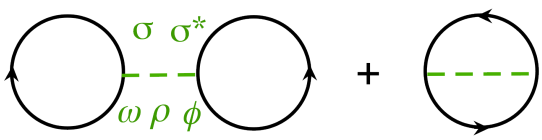
(i) Phenomenological universal YNN, YYN, YYY repulsions [S. Nishizaki, Y. Yamamotoand T. Takatsuka, Prog. Theor.Phys. 108 (2002) 703.])

(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

(2) 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)