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Properties of antikaons at highly dense matter and kaon condensation

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1. Introduction 1-1 Strangeness nuclear physics

Kaon condensation in neutron stars

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

kaon dynamics in dense matter

KN interaction

- On-shell KN scattering lengths
- kaon optical potential in nuclear matter

(kaonic atom data
Subthreshold K^+K^- production in H.I.C. / in p-nucleus collisions)

- In flight (K^-, N) KEK, BNL (analysis of missing mass spectra)
[T. Kishimoto et al., Prog. Theor. Phys. 118 (2007), 181.]

deep K^- nucleus potential, ~ – 200 MeV

controversy

Shallow potential ~ – 60 MeV in chiral unitary approach

Kaonic nuclei

(bound state of K^- meson)

[Y. Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.]
[A. Dote, H. Horiuchi et al., Phys. Lett. B 590 (2004) 51; Phys.Rev. C70 (2004) 044313.]

K^-pp state [A. Dote's talk]

1-2 Multi-strangeness system in hadronic matter

Multi-Antikaonic Nuclei

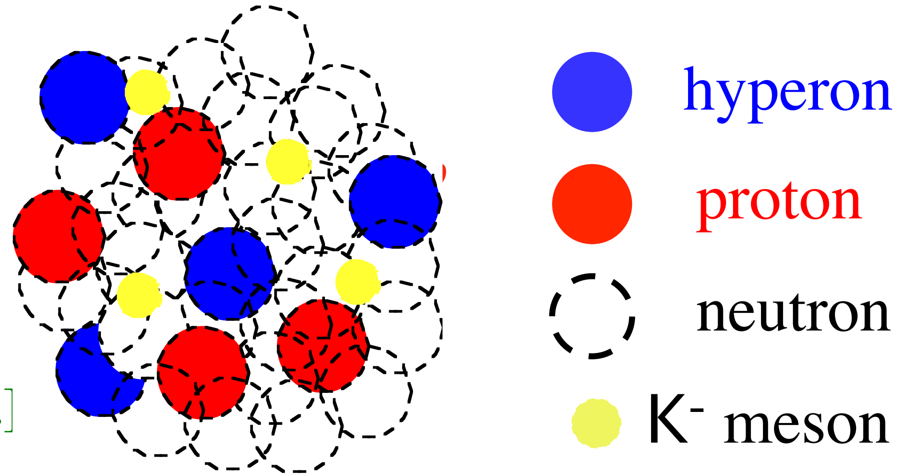
[T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]

Interaction Model: Relativistic mean-field theory (RMF) for B-B int. coupled with effective chiral Lagrangian for K-B, K-K int.

Modification of kaon dynamics with increase in strangeness

- central region: high density
- possible coexistence of antikaons and hyperons

[T. Muto, T. Maruyama and T. Tatsumi, JPS Conf. Proc. 1, 013081(2014); EPJ Web of Conferences 73, 05007 (2014).]



In neutron-stars

Kaon condensation

- Rapid cooling of neutron stars
- Softening of EOS

Hyperon-mixed matter (Λ, Σ, Ξ, ・・・ in the ground state)

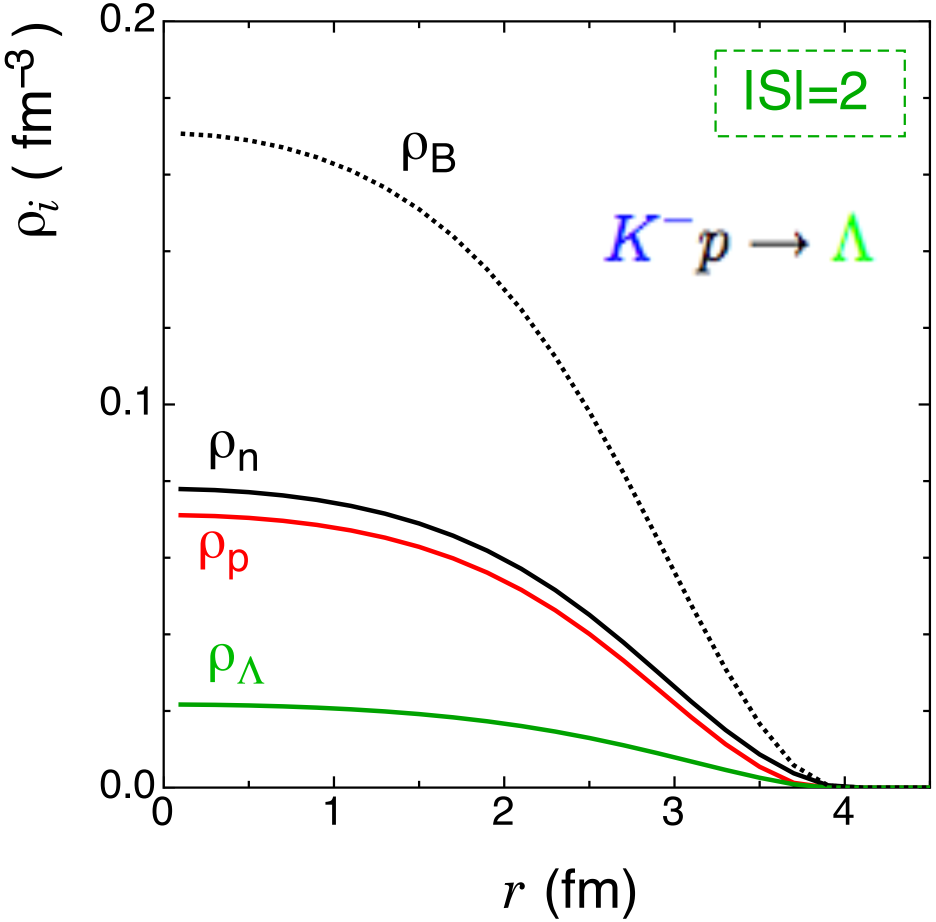
Finite nuclei

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

|S|: the number of K^- mesons embedded in nuclei

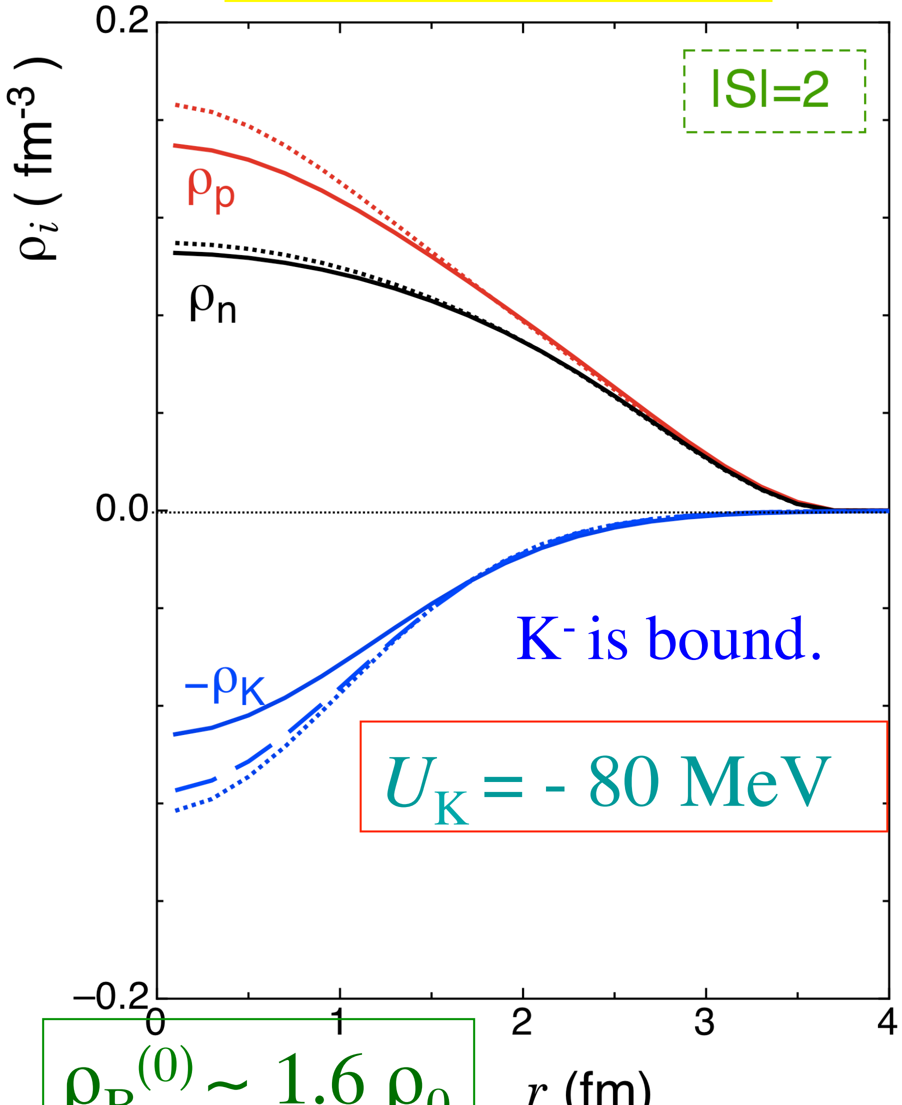
Ground state : Multi-hypernuclei

No K^- meson is bound.



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

Higher-energy state



$\rho_B^{(0)} \sim 1.6\ \rho_0$

1-2 Multi-strangeness system in hadronic matter

Multi-Antikaonic Nuclei

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

Interaction Model: Relativistic mean-field theory (RMF) for B-B int. coupled with effective chiral Lagrangian for K-B, K-K int.

Modification of kaon dynamics with increase in strangeness

- central region: high density $\rho_B \sim 3.5\ \rho_0$
- possible coexistence of antikaons and hyperons

[T. Muto, T. Maruyama and T. Tatsumi, JPS Conf. Proc. 1, 013081(2014); EPJ Web of Conferences 73, 05007 (2014).]

c.f. Meson-exchange models (MEM)

[D. Gazda, E. Friedman, A. Gal, J. Mares, Phys. Rev. C76, 055204 (2007); Phys. Rev. C77, 045206 (2008).]

In neutron-stars

Kaon condensation

Unified description of MKN in nuclei and kaon condensation in dense matter

Hyperon-mixed matter (Λ, Σ, Ξ, ・・・ in the ground state)

1-3 Coexistence of kaon condensation and hyperons [(Y+K) phase] ?

➡ theoretically $M_{max} < 2\ M_{\odot}$

⬍

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).]

For hyperon-mixed matter

Phenomenological universal YNN, YYN, YYY repulsions

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

➡ Stiffening the EOS at high densities

For kaon-B interaction

-ambiguity of S-wave $\bar{K}$-Baryon scalar interaction -

Kaon condensation

S-wave vector int. $O(m_K)$
(Tomozawa-Weinberg)

S-wave scalar int. $O(m_K^2)$
(KN sigma term)

$$\sum_B \bar{\psi}_B (i \not{\partial} - m_B)\psi_B$$
$$+ \mu \sum_B \bar{\psi}_B \gamma^0 \frac{2I_3 + 3Y}{4} \psi_B (1-\cos\theta) + \sum_B \Sigma_{KB} \bar{\psi}_B \psi_B (1-\cos\theta)$$
$$+ \frac{1}{2} f^2 (p_K)^2 \sin^2\theta - \frac{1}{2} f^2 m_K^2 (1-\cos\theta)$$

$$\theta = \frac{\sqrt{2}}{f} \langle K^- \rangle$$

+ range terms $O(m_K^2)$)
in chiral perturbation
+ $\Lambda(1405)$ pole

Regulate *S*-wave *KN* int.
by reproducing the S-wave
on-shell KN scattering lengths

uncertainty of Σ_{KN}

$$\Sigma_{KN} = \frac{1}{2}(m_u + m_s)\langle N | \bar{u}u + \bar{s}s | N \rangle$$

= (300 - 400) MeV

c.f. [H. Fujii, T. Maruyama, T. Muto, T.Tatsumi, Nucl. Phys. A 597 (1996), 645.]

We consider possible existence of (Y+K) phase in neutron stars within 2-body interaction for baryons

Effects of range terms $O(m_K^2)$ and pole contribution from $\Lambda(1405)$ on kaon-condensed EOS ?

2. Outline of the model

2-1. Baryon-Baryon interaction

Relativistic mean-field theory

Mesons: $\sigma, \omega, \rho, \sigma^*, \phi$ Baryons: $(p, n, \Lambda, \Sigma^-, \Xi^-)$

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

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

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

parameters

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

--- scalar meson couplings for Y ---

Hyperon potentials from hypernuclear experiments

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

(Λ single-particle orbitals)

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

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

(K^-, $\pi^\pm$) at BNL, (π^-, K^+) at KEK

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

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

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

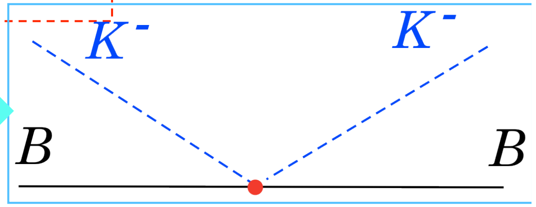
[D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175 (1986) 57.]

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

Baryons

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

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



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

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

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

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

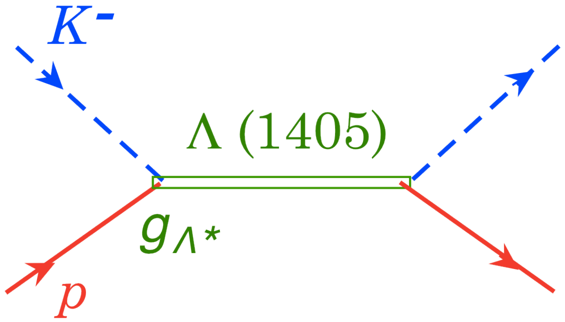
f = 93 MeV

μ_K : kaon chemical potential

2-3 Effect of Λ(1405) and range terms

$$\Delta\mathcal{L}_{KB} = \frac{d_1}{2} Tr(u_\mu u^\mu) Tr(\bar{\Psi}\Psi) + d_2 Tr(\bar{\Psi} u_\mu u^\mu \Psi)$$

+ Λ(1405) pole term



$$O(\mu^2)$$

μ : kaon chemical potential

Energy correction

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

Effective baryon masses

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

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

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

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

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

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

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

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

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

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

Experimental values from
[A.D.Martin, Nucl.Phys.A179 (1981),33.]

$$d_n = (0.584 - \Sigma_{KN}/m_K)/(f^2 m_K)$$

$$d_n = (-0.091 - \Sigma_{KN}/m_K)/(f^2 m_K)$$

$$g_{\Lambda^*} = 0.621 \qquad \gamma_{\Lambda^*} = 10.4\ \text{MeV}$$

3. Numerical Results

3-1 Kaon lowest energy ω *in hyperonic matter*

chemical equilibrium for weak processes

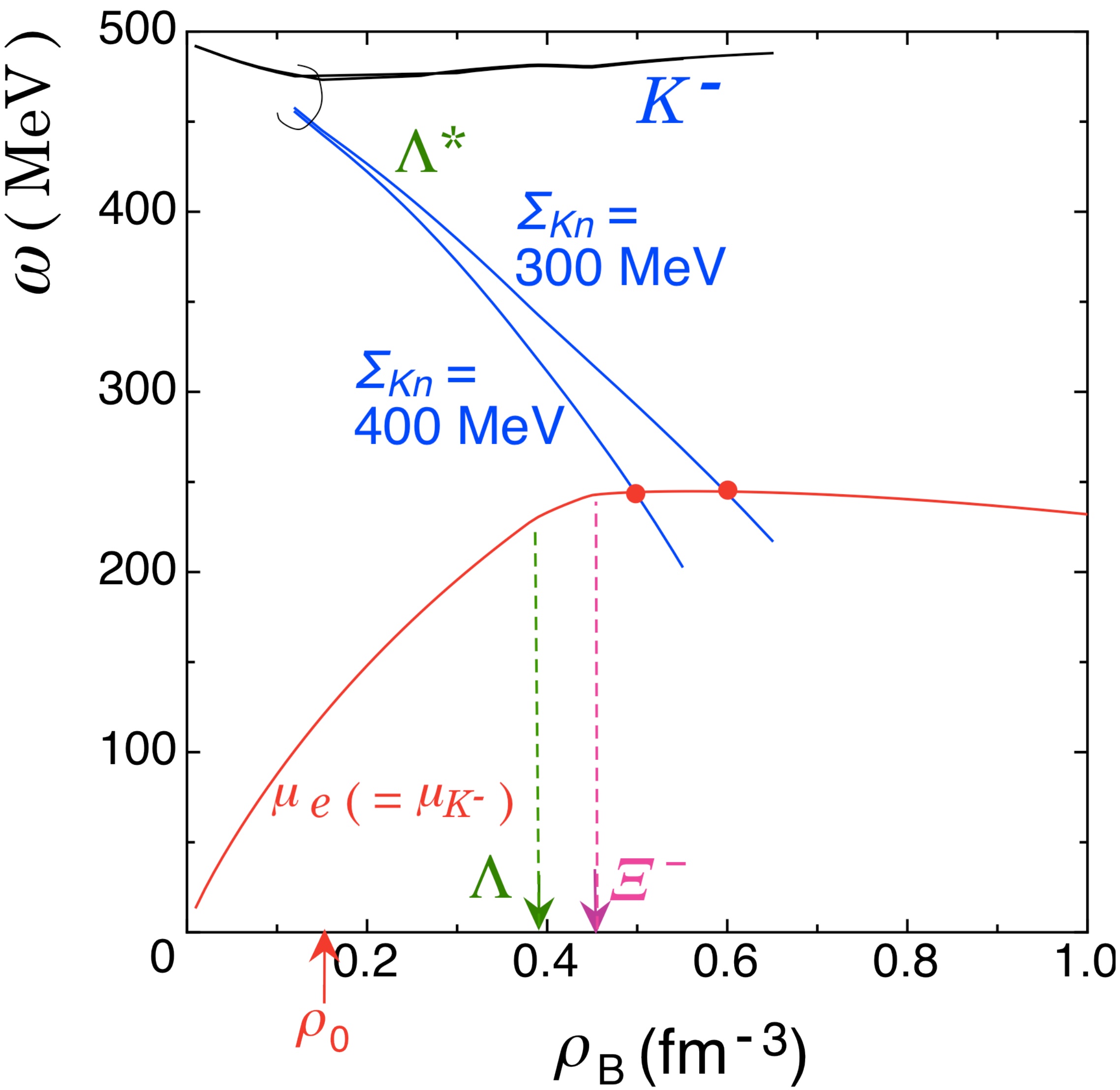
$n \rightleftharpoons p\, K^-$

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

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

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

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



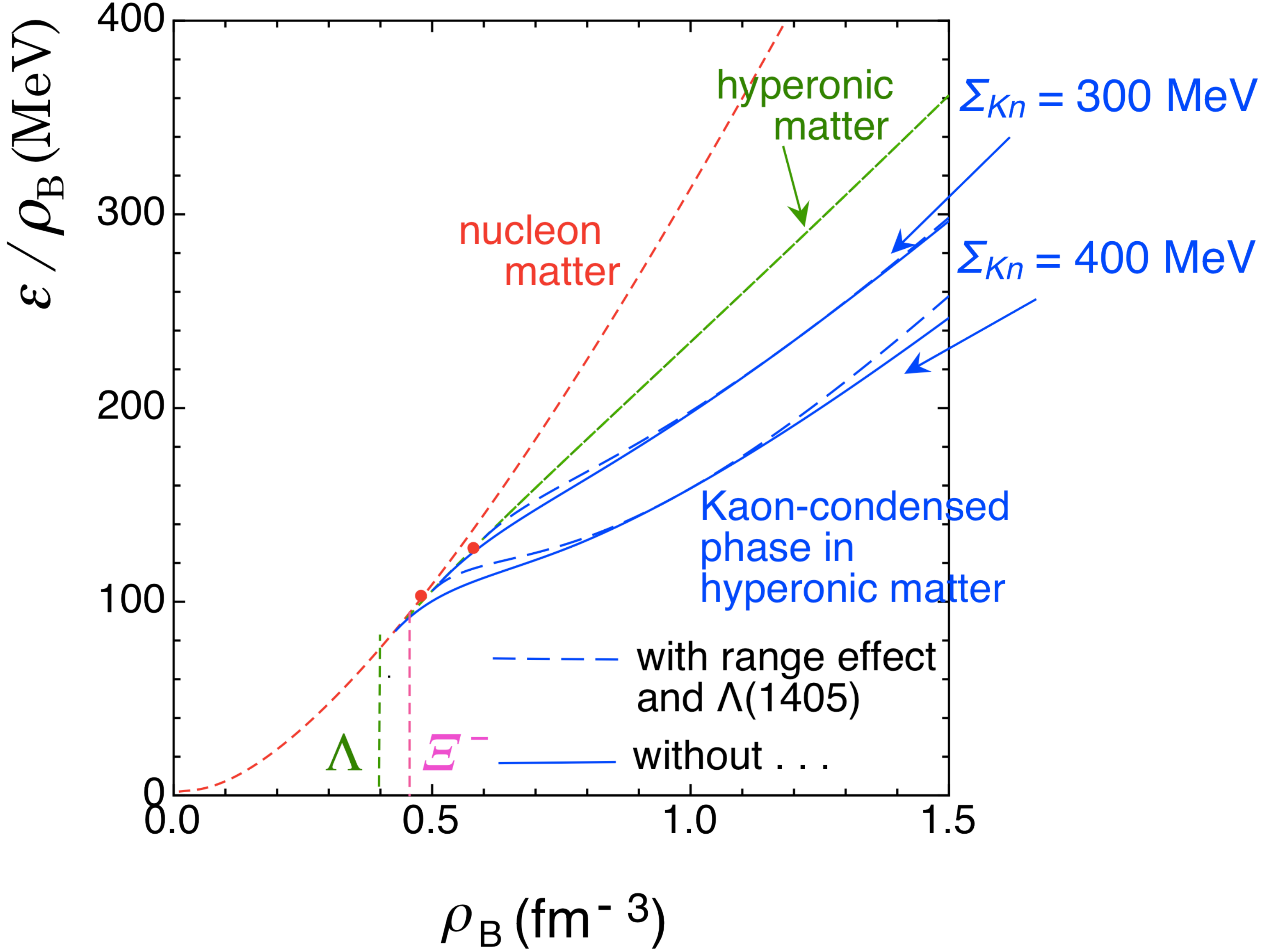
(Σ_{KN} ~ 280 MeV for <N $\bar{s}s$ |N> ~ 0)

Σ_{KN} (MeV)	U_{K^-} (MeV) at ρ_0	ρ_B^C
300	− 77	3.9 ρ_0
400	− 87	3.3 ρ_0

3. Numerical Results

3-2 EOS in β-equilibrated matter

Energy per particle



3-3 Comparison with multi-strangeness nuclei

Finite system formed in laboratory

$\omega_{K^-} = 400 \sim 450$ MeV $> \mu_\Lambda - \mu_p$ ← Finite effects of nuclei

Chemical equilibrium for strong processes

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

hard to satisfy

In neutron stars

Infinite matter

chemical equilibrium for weak processes

$n \rightleftharpoons p\, K^- \qquad p\, e^- \rightleftharpoons \Lambda\ (\nu_e) \qquad n\, e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

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

K^- chemical potential : $\omega_{K^-} = \mu = \mu_n - \mu_p$ $\quad O(m_\pi)$ for high densities

4. Discussion and summary

(1) Effects of range terms Regulate S-wave K$^-$ - B scalar attractions

- An onset density of kaon condensation is pushed up to a high density.

$\rho_B{}^C = 3.4\ \rho_0 \rightarrow 3.9\rho_0$ for Σ_{KN} = 300 MeV

$\rho_B{}^C = 2.8\ \rho_0 \rightarrow 3.3\rho_0$ for Σ_{KN} = 400 MeV

- Repulsive effect on the Kaon-condensed EOS is tiny.

(2) -- Self-suppression of scalar int. --- Relativistic effect

[H. Fujii, T. Maruyama, T. Muto, T.Tatsumi, Nucl. Phys. A 597 (1996), 645.]

Kaon condensation develops ⇒ θ : large ⇒

Effective baryon mass : decrease

$$m_i^* = m_i - g_{\sigma i}\sigma - g_{\sigma^* i}\sigma^* - \Sigma_{Ki}(1-\cos\theta)$$

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

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 K-B int.

$$-\sum_i \Sigma_{Ki}\rho_i^S(1-\cos\theta)$$

(3) 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

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

Strong repulsion between baryons at high densities are still needed.

Making EOS stiffer at high density

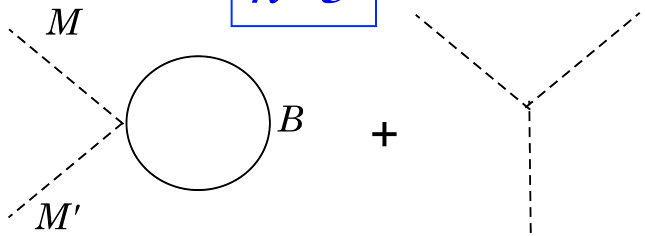
Baryon-baryon sector

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

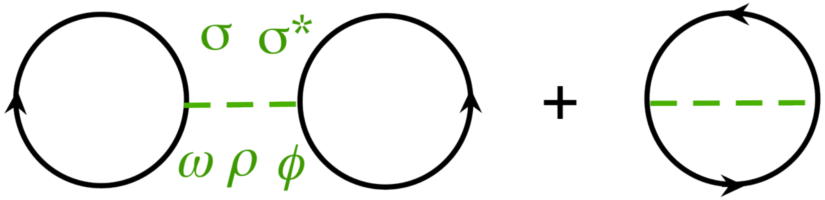
e.g., RMF extended to BMM, MMM type diagrams
[K. Tsubakihara and A. Ohnishi, arXiv:1211.7208.]
[R.J. Furnstahl, B.D. Serot, H.-B. Tang,
Nucl. Phys. A 615, 441 (1997).]

$$n = B/2 + M + D$$

n=3



(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).]



Hyperon suppression : strangeness is taken over by kaon condensates ?