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Kaon Condensation in Hyperonic Matter and Properties of Neutron Stars

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1.Introduction

Strangeness in highly dense matter

- kaon condensation (in neutron stars)

  softening of EOS,
  thermal evolution (cooling via neutrino emission)

KN interaction in nuclei

K^- optical potential

- KN data, kaonic atom data
- Subthreshold $K^+ K^-$ production in H.I.C in p-nucleus collisions

Search for deeply bound K^- nuclear states

[Y.Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.
A. Dote, Y. Akaishi et al., nucl-th/0207085.]

[T. Kishimoto, Phys. Rev. Lett.83(1999)4701.]
[M. Iwasaki et al., Nucl.Instrum.Methods Phys.Res. A473(2001) 286.]

- hyperonic matter $\rho_B^C = 2 \sim 4\ \rho_0$

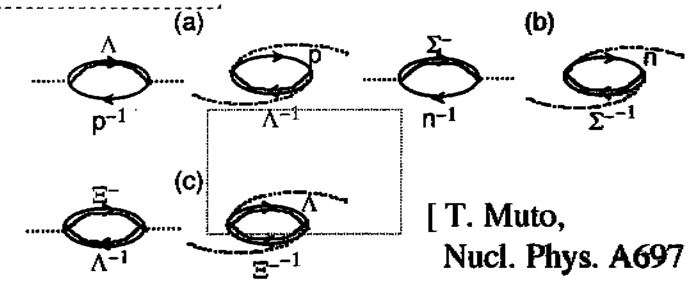
(Λ, Σ^- ・・・ in the ground state of neutron-star matter)

[M. Baldo, G.F.Burgio,H.J.Schulze, Phys.Rev.C61(2000),055801.
I. Vidana et al., Phys. Rev. C62 (2000), 035801.
S. Nishizaki, Y. Yamamoto, T. Takatsuka, Prog. Theor.Phys.105(2001),607.]

Interplay between kaon condensation and hyperons through kaon-baryon interaction

kaon condensation in hyperonic matter

Onset mechanism: P-wave KNY interactions



[T. Muto, Nucl. Phys. A697 (2002), 225.]

➡ Condensation of ($\Xi^-\Lambda^{-1}$)-($p\Lambda^{-1}$) or ($\Sigma^- n^{-1}$)-($p\Lambda^{-1}$) pairs

Equation of state

We study the equation of state of the kaon-condensed phase and clarify the resulting properties of neutron stars.

Possibility of a (metastable) kaon-condensed self-bound star

2. Formulation

$SU(3)_L \times SU(3)_R$ 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 $\psi \longrightarrow (p, \Lambda, n, \Sigma^-)$ $\quad M=\mathrm{diag}(m_u, m_d, m_u)$

Meson fields ($K^\pm$) $\quad f$ =**93 MeV**

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

$$\Pi=\pi_a T_a=\frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & K^+ \\ 0 & 0 & 0 \\ K^- & 0 & 0 \end{pmatrix} \quad V^\mu=\frac{1}{2}(\xi^\dagger\partial^\mu\xi+\xi\partial^\mu\xi^\dagger)$$
$$A^\mu=\frac{i}{2}(\xi^\dagger\partial^\mu\xi-\xi\partial^\mu\xi^\dagger)$$

Classical kaon field

$$\boxed{K^{\pm,\mathrm{cl}}(\mathbf{r},t)=\frac{f}{\sqrt{2}}\theta e^{\pm i(\mu t-\mathbf{k}\cdot\mathbf{r})}}$$

Θ:chiral angle, μ: chemical potential, k: momentum

Effective Hamiltonian

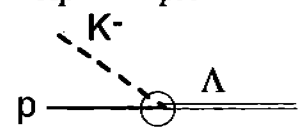
$$\mathcal{H}_{\mathrm{eff}}=\mathcal{H}+\mu(\rho_Q^B-\rho_Q^K-\rho_Q^e)=\mathcal{H}_{\mathrm{eff}}^B+\mathcal{H}_{\mathrm{eff}}^M+\mathcal{H}_{\mathrm{eff}}^e$$

Baryonic part

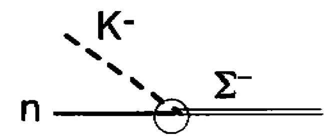
$$\begin{array}{c|c} \begin{array}{cccc} \Lambda & P & \Sigma^- & n \end{array} & \\ H_{\mathrm{eff}}^+=\begin{pmatrix} H_{\Lambda\Lambda} & H_{\Lambda p} & 0 & 0 \\ H_{p\Lambda} & H_{pp} & 0 & 0 \\ 0 & 0 & H_{\Sigma^-\Sigma^-} & H_{\Sigma^- n} \\ 0 & 0 & H_{n\Sigma^-} & H_{nn} \end{pmatrix} & \begin{array}{c} \Lambda \\ P \\ \Sigma^- \\ n \end{array} \end{array}$$

P-wave K^- -baryon int.

$H_{\Lambda p}$, $H_{p\Lambda}$



$H_{\Sigma^- n}$, $H_{n\Sigma^-}$



KNY vertex renormalization $F=\dfrac{\Lambda^2-m_K^2}{\Lambda^2+\mathbf{k}^2}$ (Λ=1~2 GeV)

[B. Holzenkamp, K. Holinde and J. Speth, Nucl. Phys. A 500 (1989) 485.]

S-wave K^- - baryon int.

- KN-sigma term (**scalar**) (Explicit chiral symmetry **breaking**)
- Tomozawa-Weinberg term (vector)

→ Quasi-particles

$$|\tilde{\Lambda}_\pm\rangle=\cos\phi\cdot|\Lambda_{\pm1/2}\rangle\pm i\sin\phi\cdot|p_{\pm1/2}\rangle$$
$$|\tilde{n}_\pm\rangle=\cos\phi'\cdot|n_{\pm1/2}\rangle\pm i\sin\phi'\cdot|\Sigma^-_{\pm1/2}\rangle$$

Baryon - Baryon Interactions

Potential energy density $\mathcal{E}_{pot}(\rho_\Lambda, \rho_p, \rho_{\Sigma^-}, \rho_n)$

[S. Balberg and A. Gal, Nucl. Phys. A625 ('97) 435]

$\Rightarrow$ Baryon potential $\boxed{V_i = \partial\mathcal{E}_{\rm pot}/\partial\rho_i}$ $(i = \Lambda, p, \Sigma^-, n)$

$$H_{ii} \to H'_{ii} = H_{ii} + V_i$$

Baryon part

$$\boxed{\mathcal{E}'^{\rm B}_{\rm eff} = \sum_i \sum_{\substack{|\mathbf{p}|\le|\mathbf{p}_F(i)| \\ s=\pm 1/2}} E'^{(i)}_s(\mathbf{p}) + \mathcal{E}_{\rm pot} - \sum_{i=p,\Lambda,n,\Sigma^-} V_i\rho_i ,}$$

meson part

$$\mathcal{E}^{\rm M}_{\rm eff} = -\tfrac{1}{2} f^2(\mu^2 - k^2)\sin^2\theta + f^2 m_{\rm K}^2(1-\cos\theta),$$

lepton part

$$\mathcal{E}^{\rm e}_{\rm eff} = \frac{\mu^4}{4\pi^2} - \mu\frac{\mu^3}{3\pi^2} = -\frac{\mu^4}{12\pi^2}$$

total energy density

$$\boxed{\mathcal{E}'_{\rm eff} = \mathcal{E}'^{\rm B}_{\rm eff} + \mathcal{E}^{\rm M}_{\rm eff} + \mathcal{E}^{\rm e}_{\rm eff}.}$$

Given ρ_B, $\boxed{\partial\mathcal{E}'_{\rm eff}/\partial\rho_i = 0}$ $(i = \tilde{\Lambda}, \tilde{p}, \tilde{\Sigma}^-, \tilde{n})$

$$\rho_{\tilde{\Lambda}} + \rho_{\tilde{p}} + \rho_{\tilde{\Sigma}^-} + \rho_{\tilde{n}} = \rho_B$$

$$\Vert$$

$$\mu_{\tilde{\Lambda}} = \mu_{\tilde{p}} = \mu_{\tilde{\Sigma}^-} = \mu_{\tilde{n}}$$

Parameters $\quad \delta = \gamma = 5/3$

Saturation property of symmetric nuclear matter

- $\rho_0 = 0.16\ {\rm fm}^{-3}$
- binding energy =16 MeV
- incompressivility =210 MeV

$\Rightarrow$ $a_{NN} = -859.5({\rm MeV\cdot fm^3})$, $c_{NN} = 1300.8({\rm MeV\cdot fm^{3\gamma}})$

symmetry energy at ρ_0 $\Rightarrow$ $b_{NN} = 212.8({\rm MeV\cdot fm^3})$

depth of V_Λ =-27 MeV $\Rightarrow$ $a_{\Lambda N}\rho_0 + c_{\Lambda N}\rho_0^\gamma = -27{\rm MeV}$

Λ single-particle orbitals $\Downarrow$

$$a_{\Lambda N} = -387.0({\rm MeV\cdot fm^3})$$

$$c_{\Lambda N} = 738.8({\rm MeV\cdot fm^{3\gamma}})$$

[D. J. Millener, C. B. Dover and A. Gal, Phys. Rev. C38 (1998), 22700.]

V_{Σ^-} potential

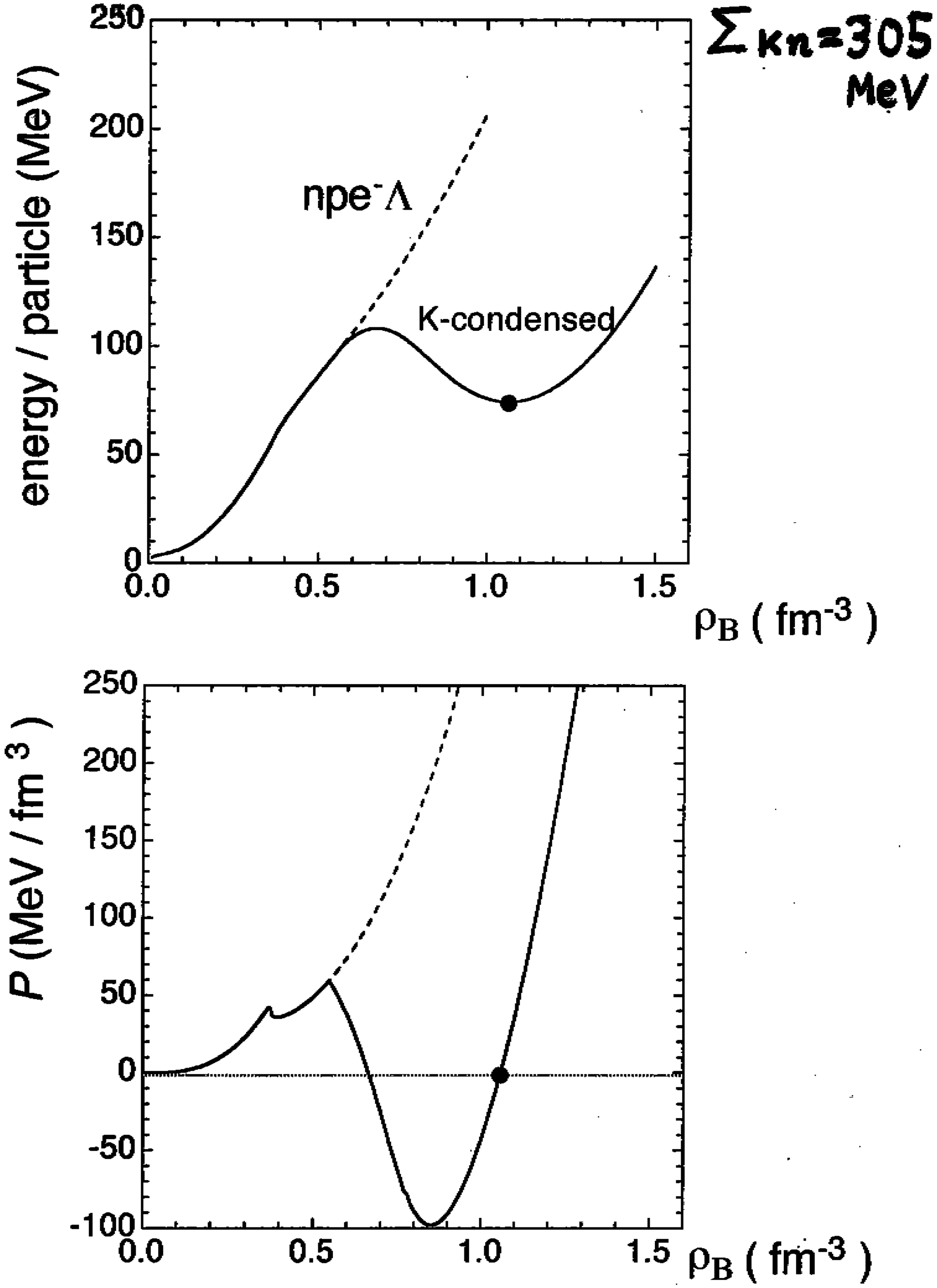
(1) repulsive case

[J. Dabrowski, Phys. Rev. C60 (1999), 025205.]

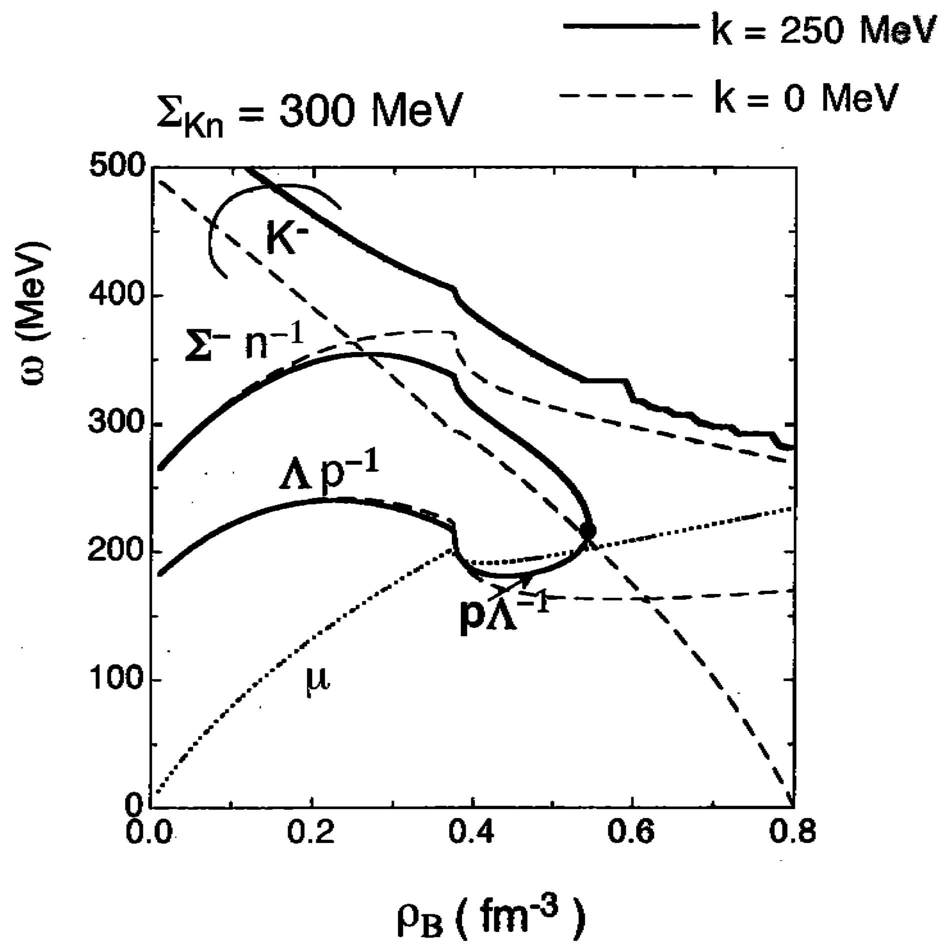
$$V_{\Sigma^-}(k_\Sigma) = V_0(k_\Sigma) - \frac{1}{2}V_1(k_\Sigma)\cdot\frac{Z-N}{A}$$

$$a_{\Sigma N}\rho_0 + c_{\Sigma N}\rho_0^\gamma = V_0 = 23.5{\rm MeV}$$

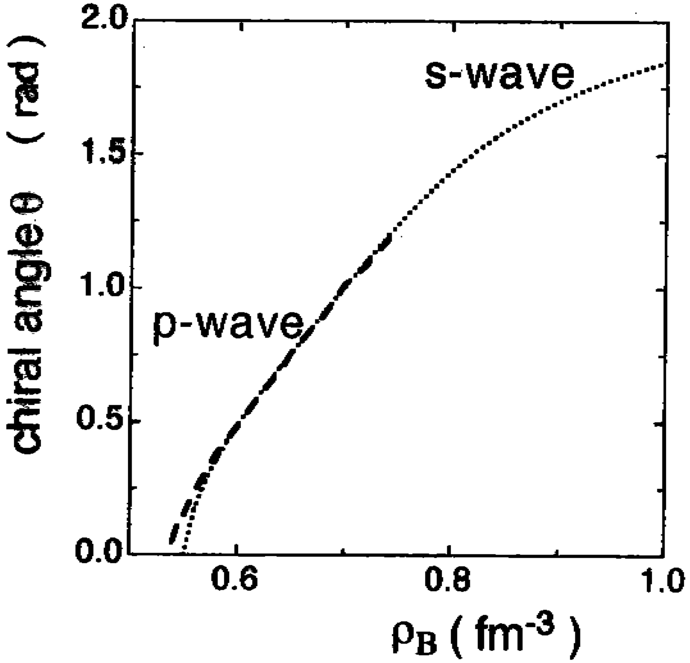
$$b_{\Sigma N}\rho_0 = \frac{1}{2}V_1 = 40.2{\rm MeV}$$

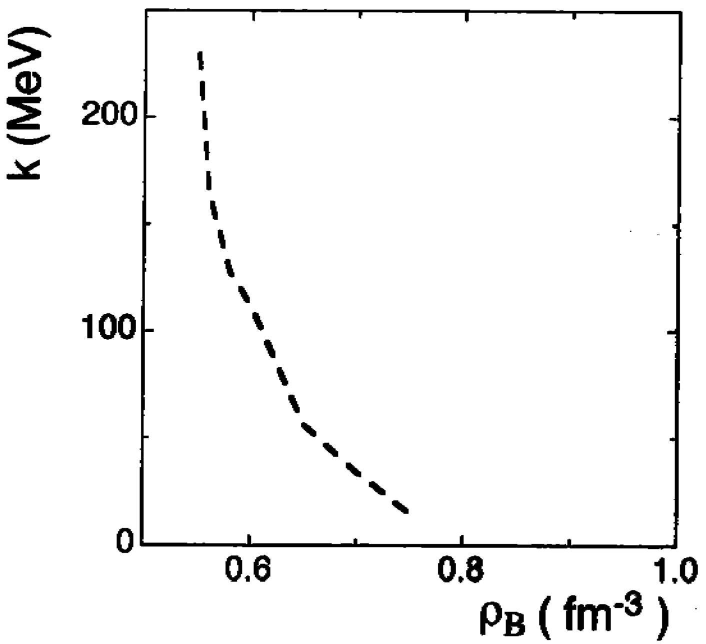


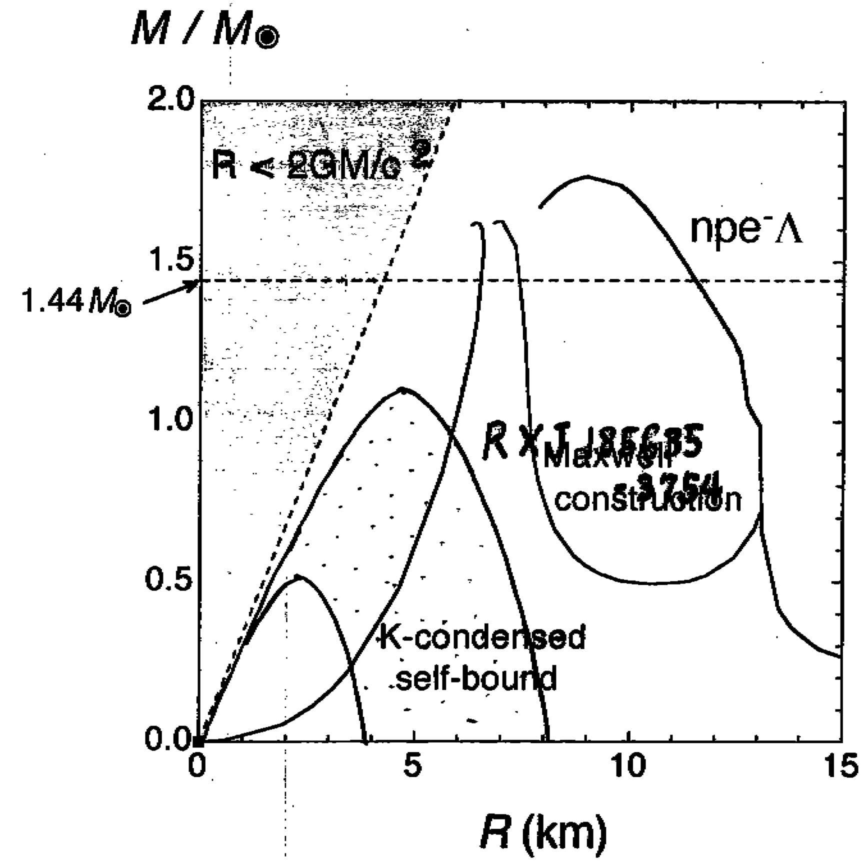
Σkn=305 MeV
energy / particle (MeV)
npe⁻Λ
K-condensed
P (MeV / fm 3)
ρB (fm-3)



k = 250 MeV
k = 0 MeV
ΣKn = 300 MeV
K-
Σ- n-1
Λ p-1
pΛ-1
μ
ω (MeV)
ρB (fm-3)







[J. J. Drake et al.,
Astrophys. J 572 (2002) 996.

$$R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$$

4. Summary and concluding remarks

We have studied the equation of state (EOS) with kaon condensation in hyperonic matter and its effects on neutron-star structure. We have taken into account the p-wave kaon-baryon interactions as well as the s-wave ones on the basis of chiral symmetry, and have used the nonrelativistic effective baryon-baryon interactions.

Results

At a critical density, ($\rho_B^{C} \sim 3.5\ \rho_0$)

The system becomes unstable with respect to a pair creation of collective modes with K^+ and K^- quantum numbers (pair condensation), which originates from the p-wave kaon-baryon interactions.

EOS of the condensed phase

- In the well-developed phase, the s-wave kaon-baryon attractions are dominant as compared with the p-wave ones.
- much softening due to kaon condensation in addition to that due to hyperons

↓

The energy of the system has a local minimum with respect to a baryon number density.
The pressure becomes negative in certain density interval.

→ Possibility of a (metastable) kaon-condensed self-bound star

→ Kaon dynamics in highly dense matter

Future problems

Suppression effects of softening of EOS

- relativistic effects

(suppression of the s-wave scalar attraction at high densities)

RMF theories

[H. Fujii, et al., Nucl. Phys. A 597 (1996) 645.
S. Banik and D. Bandyopadhyay,
Phys. Rev. C 64 (2001) 055805.
Phys. Rev. C 66 (2002) 065801.]

- form of effective baryon-baryon interactions

repulsive three-body forces between hyperons and nucleons
[S. Nishizaki, Y. Yamamoto and T. Takatsuka,
Prog. Theor. Phys. 108 (2002) 703.]

- short-range correlations between baryons

[E. E. Kolomeitsev and D. N. Voskresensky,
Phys. Rev. C68 (2003) 015803.]

Subthreshold baryons $\Lambda(1405)$, $\Sigma(1385)$ · ·

Formation scenario for a self-bound kaon-condensed star