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Effects of Λ(1405) on the Structure of Multi-Antikaonic Nuclei

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1. Introduction

Multi-strangeness system in hadronic matter

Kaonic nuclei (bound state of single K^- meson)

- theoretical prediction [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.]
- experimental search
  - ^{4}He (K^- stopped, p), ^{4}He (K^- stopped, n) (KEK, J-PARC)
  - In flight (K^-, N) (KEK, BNL)
  - K^- pp state (FINUDA) (DISTO Collaboration)

|S| = 0, 1, 2, 3, ・・

Multi-Antikaonic Nuclei → (Cold and dense matter) → **Kaon condensation**

in laboratory (finite system) — in neutron-stars (infinite matter)

- similarity of KN, KK interactions
  (Chiral symmetry)
- difference of production mechanisms

Strangeness-conserving system ↔ **Strangeness-nonconserving system**

``strangeness is given''

$$n \rightleftharpoons p\, K^-$$

Chemical equilibrium for weak processes

``strangeness is spontaneously produced''

Chiral model

Properties of Multi-$\bar{K}$ nuclei (MKN)

RMF (σ, ω, ρ exchange)
+ $\bar{K}$-N, $\bar{K}$-$\bar{K}$ interactions based on chiral symmetry

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

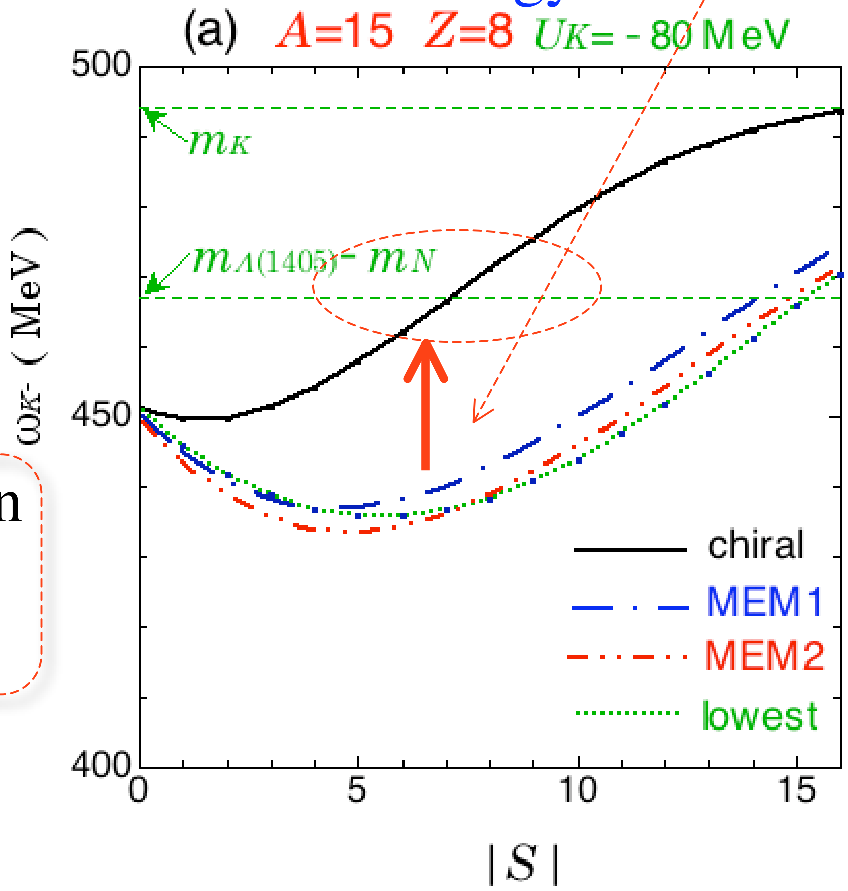
↕

Meson-exchange models (MEM)

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

nonlinear $\bar{K}$-$\bar{K}$ int.
(repulsive)

K^- energy



|S|: Number of embedded K^-

K^- energy enters into Resonance region of Λ(1405)

We study effects of pole contribution of Λ(1405) on the structure of the MKN

- density distributions of p, n, K^-
- K^- field amplitude, central density, binding energy, ···

2. Formulation

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

[M. Yasuhira and T. Tatsumi, Nucl. Phys. A690 (2001) 769.]

2-1 Chiral Model

nonlinear chiral effective Lagrangian

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

Baryons Ψ → (p, n)

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

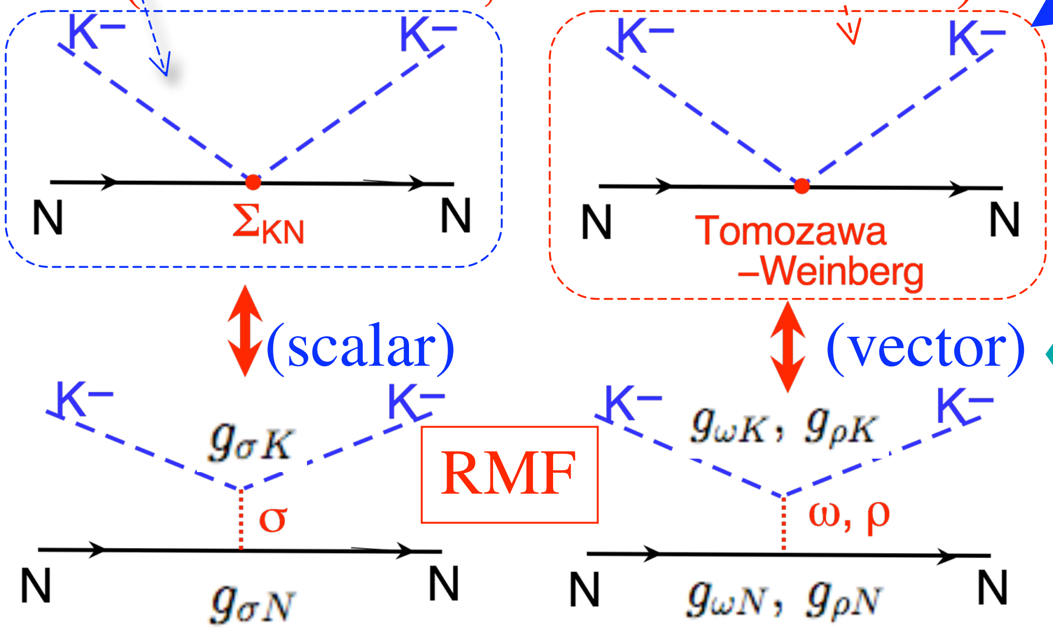
$$f = 93 \text{ MeV}$$

kaon fields ($K^\pm$)
(nonlinear representation)

$$\Sigma \equiv e^{2i\Pi/f}$$

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

(S-wave K-N, K-K interactions)



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

(KN sigma term)

$$\frac{g_{\omega N} g_{\omega K}}{m_\omega^2} = \frac{3}{8f^2} \qquad \frac{g_{\rho N} g_{\rho K}}{m_\rho^2} = \frac{1}{8f^2}$$

(Tomozawa-Weinberg)

2.2 Effects of Range terms and Λ(1405) (Second-order effects, SOE)

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

Correction to thermodynamic potential

axial current of hadrons : $A_5^\mu = f\partial^\mu K^- + \cdots + \frac{g_{\Lambda^*}}{2}(\bar{\Lambda}^*\gamma^\mu p + \mathrm{h.c.}) + \cdots$

$$\Delta\epsilon = -i\int d^4z\langle x|T\widetilde{\omega}_{K^-}\hat{A}_5^0(z)\widetilde{\omega}_{K^-}\hat{A}_5^0(0)|x\rangle \times \left(-\frac{1}{2}\sin^2\theta\right)$$

range terms

real part ⇒

$$-\frac{1}{2}f^2\widetilde{\omega}_{K^-}^2\sin^2\theta\left[\rho_p^s\left\{d_p + \frac{g_{\Lambda^*}{}^2}{2f^2}\frac{m_{\Lambda^*}-m_N-\omega_{K^-}}{(m_{\Lambda^*}-m_N-\omega_{K^-})^2+\gamma_{\Lambda^*}^2}\right\} + d_n\rho_n^s\right] ;$$

pole term Λ(1405)

Effective nucleon mass

$$m_p^* = m_N - g_{\sigma N}\sigma - \frac{1}{2}f^2\widetilde{\omega}_{K^-}^2\sin^2\theta\left\{d_p + \frac{g_{\Lambda^*}{}^2}{2f^2}\frac{m_{\Lambda^*}-m_N-\omega_{K^-}}{(m_{\Lambda^*}-m_N-\omega_{K^-})^2+\gamma_{\Lambda^*}^2}\right\}$$

$$m_n^* = m_N - g_{\sigma N}\sigma - \frac{1}{2}f^2\widetilde{\omega}_{K^-}^2\sin^2\theta\cdot d_n .$$

Choice of parameters

$$d_p = \left(0.35 - \frac{\Sigma_{KN}}{m_K}\right)/(f^2 m_K) \quad g_{\Lambda^*} = 0.58$$

$$d_n = \left(0.23 - \frac{\Sigma_{KN}}{m_K}\right)/(f^2 m_K) \quad \gamma_{\Lambda^*} = 12.35\ \mathrm{MeV}$$

S-wave on-shell KN scattering lengths

[A. D. Martin, Nucl. Phys. B 179 (1981) 33.]

$a(K^-p) = -0.67 + i0.64$ fm

$a(K^-n) = 0.37 + i0.60$ fm

$a(K^+p) = -0.33$ fm $a(K^+n) = -0.16$ fm

Local density approximation for nucleons

(coherent state)

$$\langle K^- \rangle = \frac{f}{\sqrt{2}} \theta(\mathbf{r})$$

K$^-$ field equation

・nonlinear $\bar{K}$-$\bar{K}$ int.

$$\nabla^2\theta = \sin\theta \Big[m_K^{*2} - 2\widetilde{\omega}_{K^-} X_0 - \widetilde{\omega}_{K^-}^2 \cos\theta - \widetilde{\omega}_{K^-}^2 \cos\theta \Big\{ \rho_p^s \Big(d_p + \frac{g_{\Lambda^*}{}^2}{2f^2} \frac{m_{\Lambda^*} - m_N - \omega_{K^-}}{(m_{\Lambda^*} - m_N - \omega_{K^-})^2 + \gamma_{\Lambda^*}^2} \Big) + d_n \rho_n^s \Big\} \Big]$$

$$m_K^{*2} = m_K^2 - 2g_{\sigma K} m_K \sigma \qquad X_0 = g_{\omega K}\omega_0 + g_{\rho K} R_0$$

Equations of motion for mesons

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

$$-\nabla^2\omega_0 + m_\omega^2\omega_0 = g_{\omega N}(\rho_n + \rho_p) + 2f^2 g_{\omega K}(\cos\theta - 1)(\omega_K - V_{\mathrm{Coulomb}})$$

Lowest energy of K$^-$

$$-\nabla^2 R_0 + m_\rho^2 R_0 = g_{\rho N}(\rho_p - \rho_n) + 2f^2 g_{\rho K}(\cos\theta - 1)(\omega_K - V_{\mathrm{Coulomb}})$$

$$\nabla^2 V_{\mathrm{Coulomb}} = 4\pi e^2 \rho_{\mathrm{ch}}$$

2.3 Choice of parameters

Reproduce 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

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

$g_{\omega K} = g_{\omega N}/3$
$g_{\rho K} = g_{\rho N}$
← quark and isospin counting rule

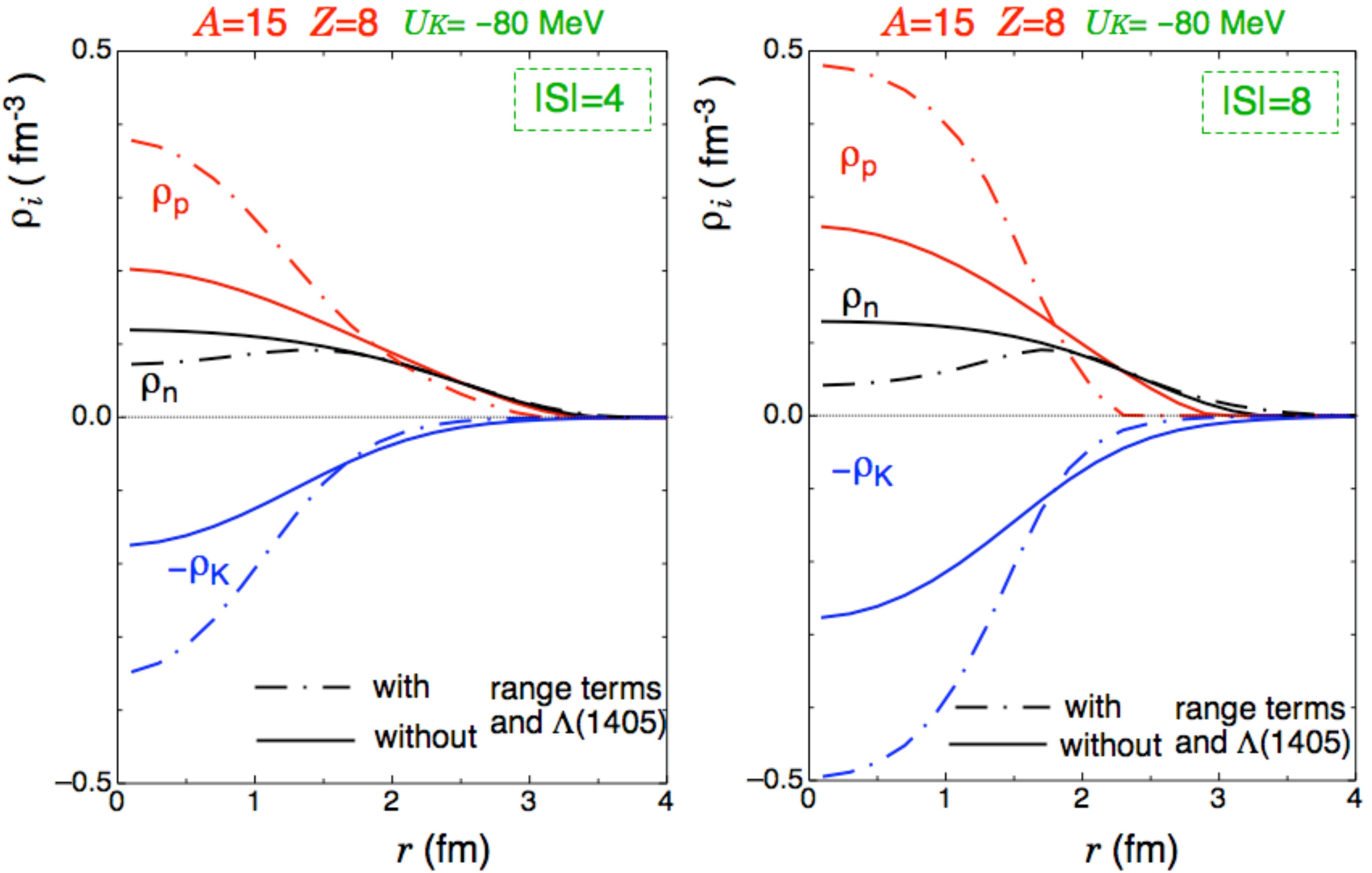
$g_{\sigma K}$ ← $U_K = -(g_{\sigma K}\sigma + g_{\omega K}\omega_0)$ at ρ_0 in symmetric nuclear matter

U_K(MeV)	$g_{\sigma K}$	$g_{\omega K}$	$g_{\rho K}$	$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	m_σ (MeV)
−80	0.97	2.91	4.27	6.39	8.72	4.27	400
−120	2.21	"	"	"	"	"	"
D. Gazda et al.	1.22	3.02	3.02	10.44	12.96	4.38	526

for ^{20}O+|S| K^-

3. Numerical results ------- Chiral model ------- U_K= - 80 MeV

Effects of range terms and Λ(1405) on density distributions



Contribution to the effective nucleon mass

$$m_p^* = m_N - g_{\sigma N}\sigma + \Delta m_p(\text{range}) + \Delta m_p(\Lambda(1405))$$

$$\Delta m_p(\Lambda(1405)) =$$

$$-\frac{1}{2} f^2 (\omega_{K^-} - V_{\text{Coul.}})^2 \sin^2\theta \cdot \frac{{g_{\Lambda^*}}^2}{2f^2} \frac{m_{\Lambda^*} - m_N - \omega_{K^-}}{(m_{\Lambda^*} - m_N - \omega_{K^-})^2 + \gamma_{\Lambda^*}^2} < 0$$

(attractive for $\omega_{K^-} < m_{\Lambda^*} - m_N$)

$$\Delta m_p(\text{range}) =$$

$$-\frac{1}{2} f^2 (\omega_{K^-} - V_{\text{Coul.}})^2 \sin^2\theta \cdot d_p > 0$$

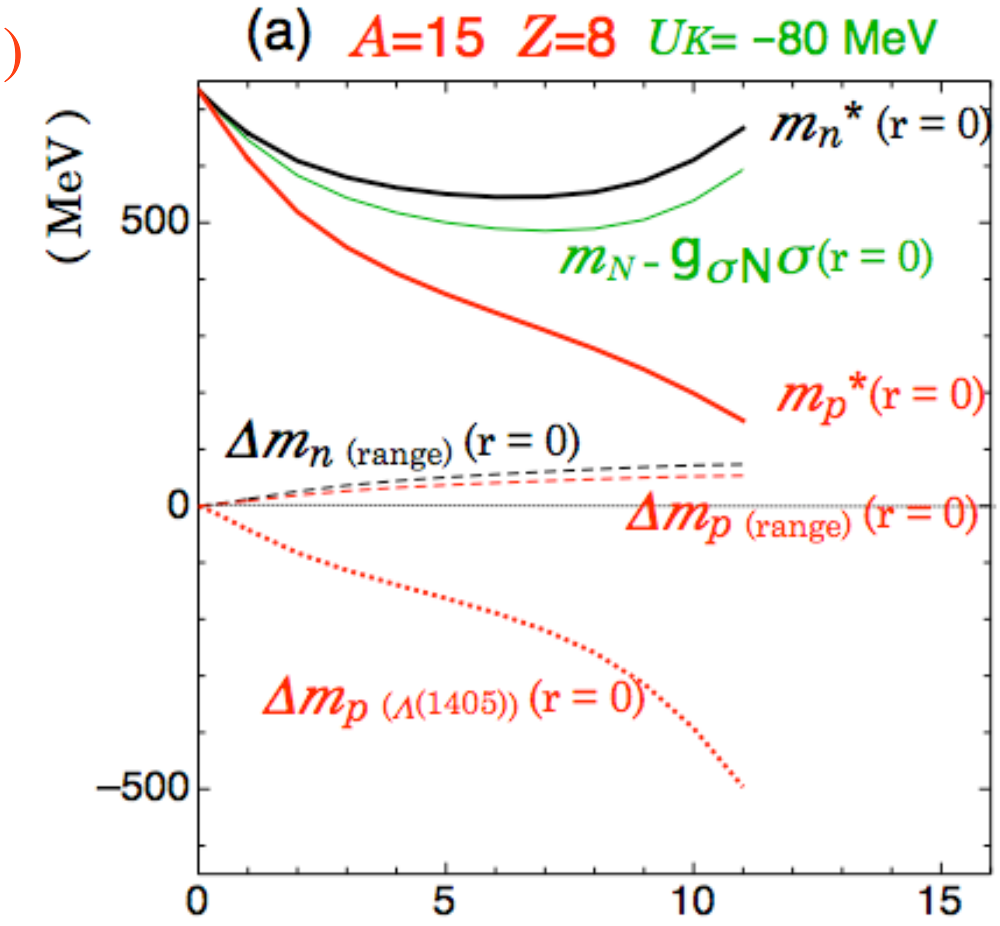
(repulsive)

$$m_n^* = m_N - g_{\sigma N}\sigma + \Delta m_n(\text{range})$$

$$\Delta m_n(\text{range}) =$$

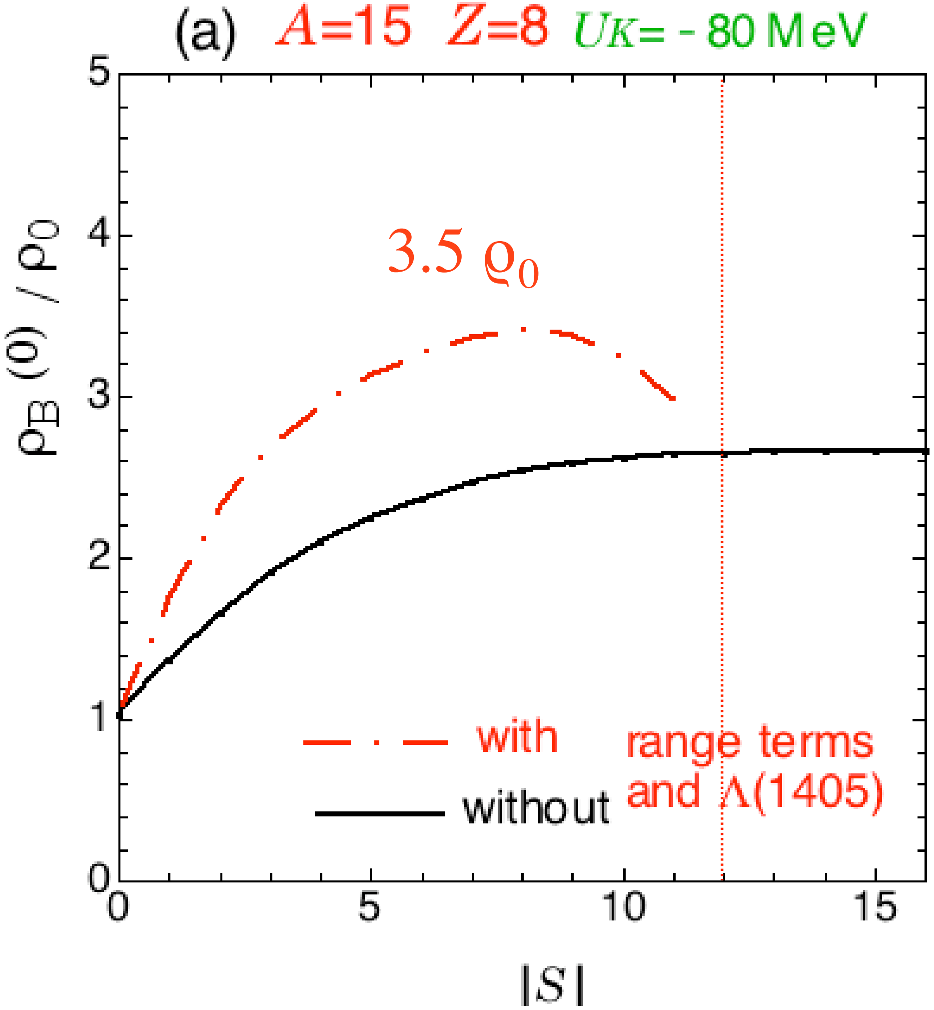
$$-\frac{1}{2} f^2 (\omega_{K^-} - V_{\text{Coul.}})^2 \sin^2\theta \cdot d_n > 0$$

(repulsive)

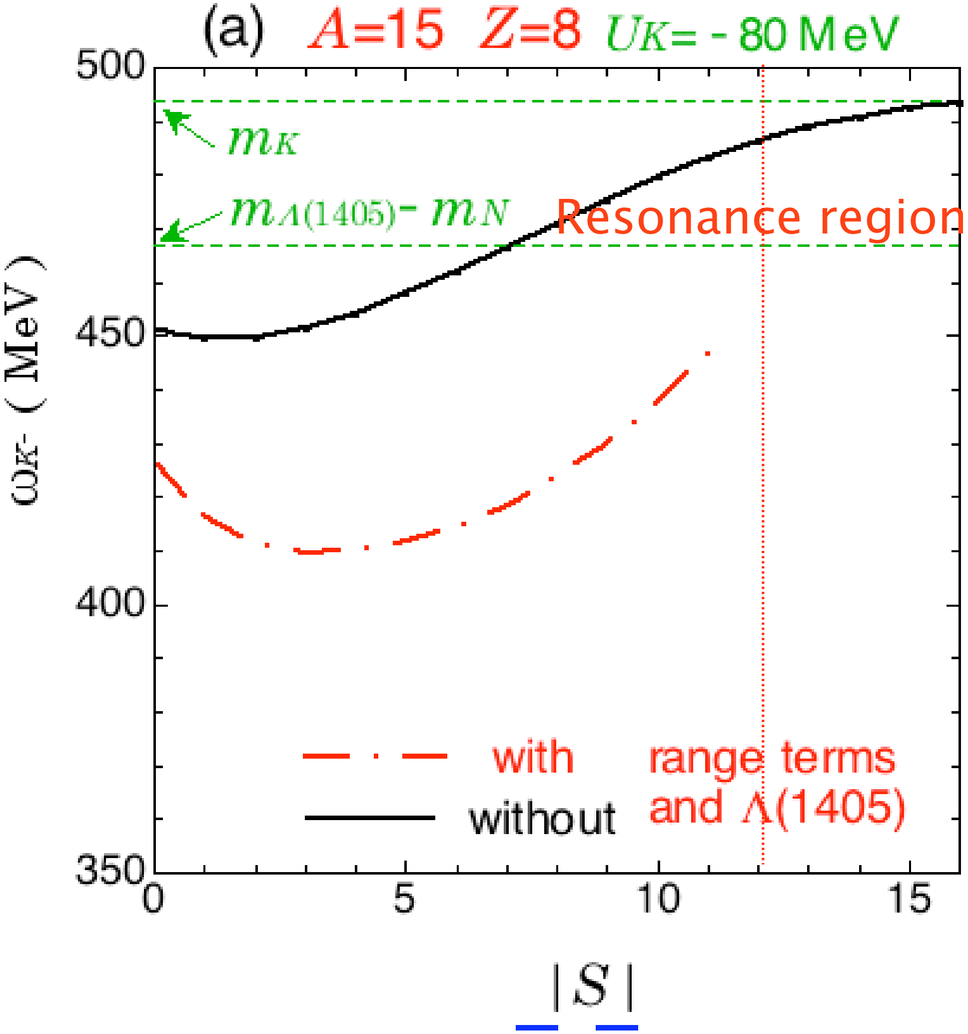


|S|: the number of trapped K-

baryon density $\varrho_B\ (r=0)\ /\ \varrho_0$



lowest K^- energy ω_{K^-}



With increase in |S|, ω_{K^-} increases due to the repulsive $\bar{K}$-$\bar{K}$ interaction.

For |S| ≧ 12, K^- mesons become unbound with $\omega_{K^-} \gtrsim m(1405) - m_N$

(above the resonance region)

4. Summary and outlook

We have studied the structure of multi-antikaonic nuclei (MKN) in the relativistic mean-field theory by taking into account kaon dynamics on the basis of chiral symmetry.

Second-order Effects (SOE)

(i) pole contribution of Λ(1405) to K^- p int.

(ii) Range terms ($\propto d_p \omega_{K^-}^2, \quad d_n \omega_{K^-}^2$)

Due to the attractive interaction from the Λ(1405)-pole contribution (i), K^- and proton are more attracted each other than the case without SOE.

- Central densities of K^- and proton become larger.
  ($\rho_B^{(0)} = 3.5\ \rho_0$ for U_K=-80 MeV)) ($\rho_B^{(0)} = 3.8\ \rho_0$ for U_K=-120 MeV)
- Density distributions for K^- and proton become more uniform.

Density distribution for neutron is pushed outward due to the repulsive effect from the range term (ii).

neutron skin 1~2 fm for |S|= 4~10.

remarkable for large |S|

Future problems

ambiguity of kaon - baryon attractive interaction

- $g_{\sigma K}$: (s-wave scalar attraction Σ_{KN} term) <----- U_K

  $g_{\omega K}$, $g_{\rho K}$: s-wave vector int. < ----- ・quark model,
  - vector-meson dominance
  - contribution from Φ meson

role of hyperons (Y)

- inelastic channel coupling effects (kaon decay width . . .)

$$\bar{K}N \to \pi\Lambda, \pi\Sigma$$

- Hyperon -mixing effects --- a possibility of more strongly bound states (coexistence of antikaons and hyperons) [T. Muto, Phys. Rev. C 77 (2008) 015810; Nucl. Phys. A804 (2008) 322.]

Microscopic effects (shell structure, clustering structure . . .)

possible observation of multi $\bar{K}$ nuclei produced in experiments (heavy-ion collisions, J-PARC, GSI FAIR, ・・・)

- information of $\bar{K}$-$\bar{K}$ interactions