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Session 2B

Effect of Λ(1405) on structure of multi-antikaonic nuclei

Takumi Muto (Chiba Institute of Technology)

collaborators: Toshiki Maruyama (JAEA)
Toshitaka Tatsumi (Kyoto University)

1. Introduction Strangeness relevant to K^- mesons

Kaonic nuclei Highly dense and low temperature object

Theoretical prediction based on deep K^- potential

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

kaonic nuclei by AMD [A. Dote, H. Horiuchi et al., Phys. Lett. B 590 (2004) 51; Phys.Rev. C70 (2004) 044313.]

⟷ Sharrow potential ~ 60 MeV in chiral unitary approach

Experimental searches

- ^{4}He (K^- stopped, p), ^{4}He (K^- stopped, n) KEK, J-PARC [M. Iwasaki et al. T. Suzuki et al., Phys. Rev. C76, 068202(2007).]
- In flight (K^-, N) KEK, BNL [T. Kishimoto et al., Prog. Theor. Phys. 118 (2007), 181.]

  deep K-nucleus potential, ~200 MeV (analysis of missing mass spectra)
- K^- pp state FINUDA [M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303; Phys. Lett. B654(2007), 80.]

  DISTO Collaboration [T. Yamazaki et al., arXiv: 1002.3526v1 [nucl-ex].]]

For a recent review,

[A. Gal, R. S. Hayano (Eds.), Nucl. Phys. A804 (2008).]

[E. Oset, V.K.Magas, A. Ramos, S. Hirenzaki, J. Yamagata-Sekihara, A.Martinez Torres, K.P.Khemchandani, M. Napsuciale, L.S. Geng, D. Gamermann, arXiv: 0912.3145v1[nucl-th].]

Multi-strangeness system in hadronic matter

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

$|S| = 0, 1, 2, 3, \cdots$

Strangeness-conserving system

``the number of strangeness $|S|$ is fixed''

Multi-Antikaonic Nuclei (MKN)

in laboratory (finite system)

relativistic mean-field theory (RMF)

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

- central region: high density $\rho_B \sim 3.5\ \rho_0$
- outer region: neutron skin

Meson-exchange models (MEM)

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

Asymmetry in Neutron-Rich Nuclei

- incompressibility
- symmetry energy

High-density hadronic matter

in neutron stars

$\bar{K}-N$ and $\bar{K}-\bar{K}$ interactions at high-baryon densities : relevance to Kaon condensation

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

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

K^- energy enters into the Resonance region of $\Lambda(1405)$ (Λ^*).

We take into account the Λ^* and study roles of a Λ^* -pole contribution on the structure of the MKN.

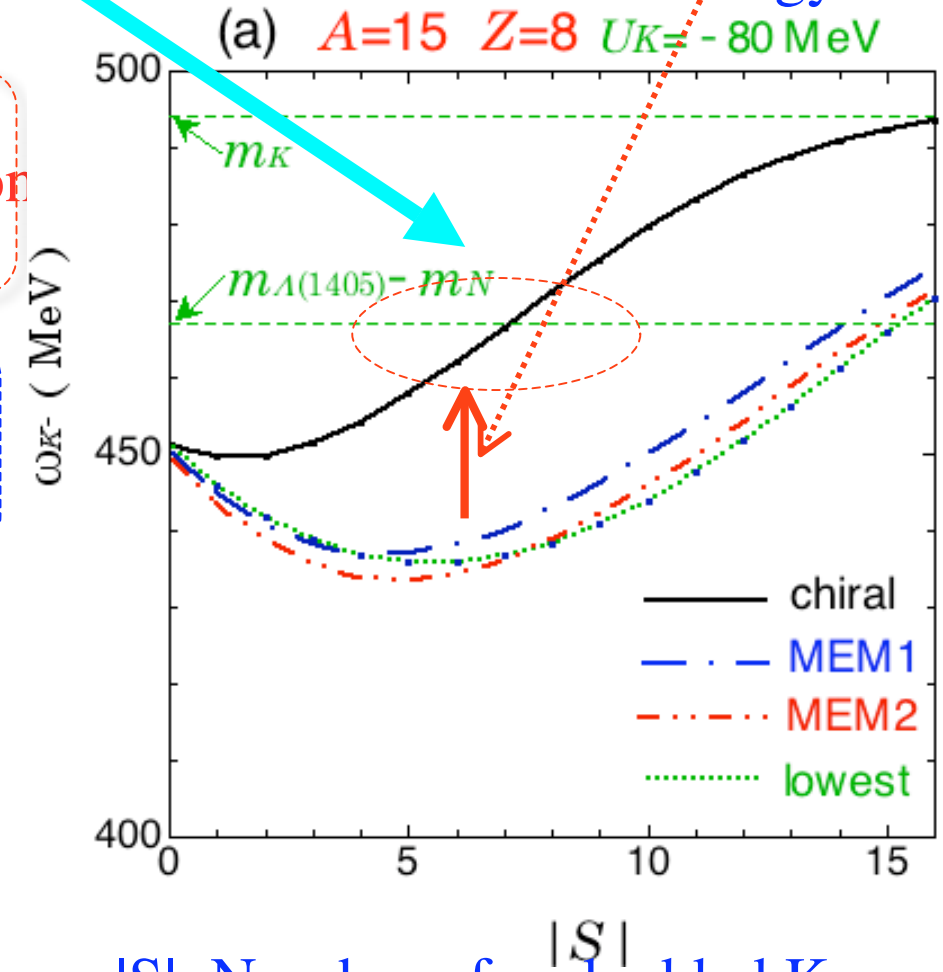
- density distributions of p, n, K^-
- K^- field amplitude, central density, binding energy, …

c.f.
- the I=0 $\bar{K}N$ bound state
- two-pole structure

[E. Oset, A. Ramos, C. Bennhold, Phys. Lett. B527 (2002), 99.
T. Hyodo and W.Weise, Phys. Rev. C77, 035204 (2008).]

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

Previous result on K^- energy



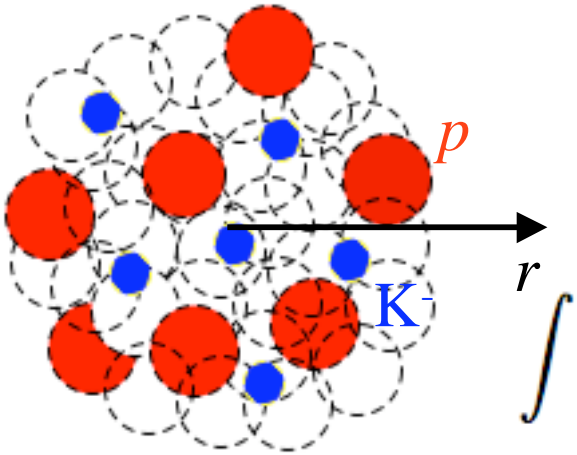
|S|: Number of embedded K^-

2. Formulation

2-1 Outline of MKN

Assume : Spherical symmetry

Multi-$\bar{K}$ Nuclei



$A = N + Z$: mass number

Z: the number of proton

$|S|$: the number of the embedded K^-

fixed

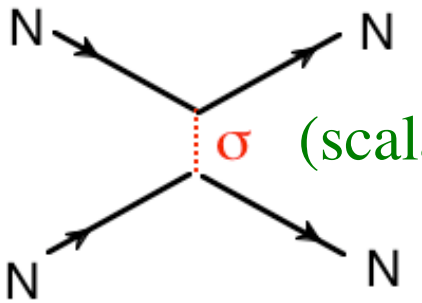
constraints

$$\int \rho_p(\mathbf{r})d^3r = Z \quad \int \rho_n(\mathbf{r})d^3r = N \quad \int \rho_K(\mathbf{r})d^3r = |S|$$

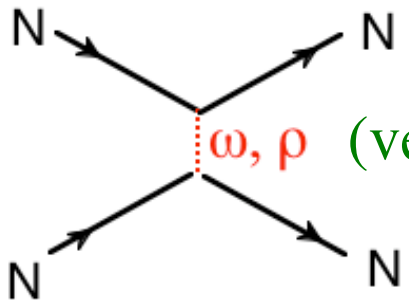
Local density approximation for nucleons

2-2 Interactions

Model for N-N interaction : Relativistic Mean-Field (RMF) theory



(scalar)



(vector)

2-3 $\bar{K}-N, \bar{K}-\bar{K}$ interactions

nonlinear chiral effective Lagrangian

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

Baryons $\psi \Longrightarrow$ (p, n)

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

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

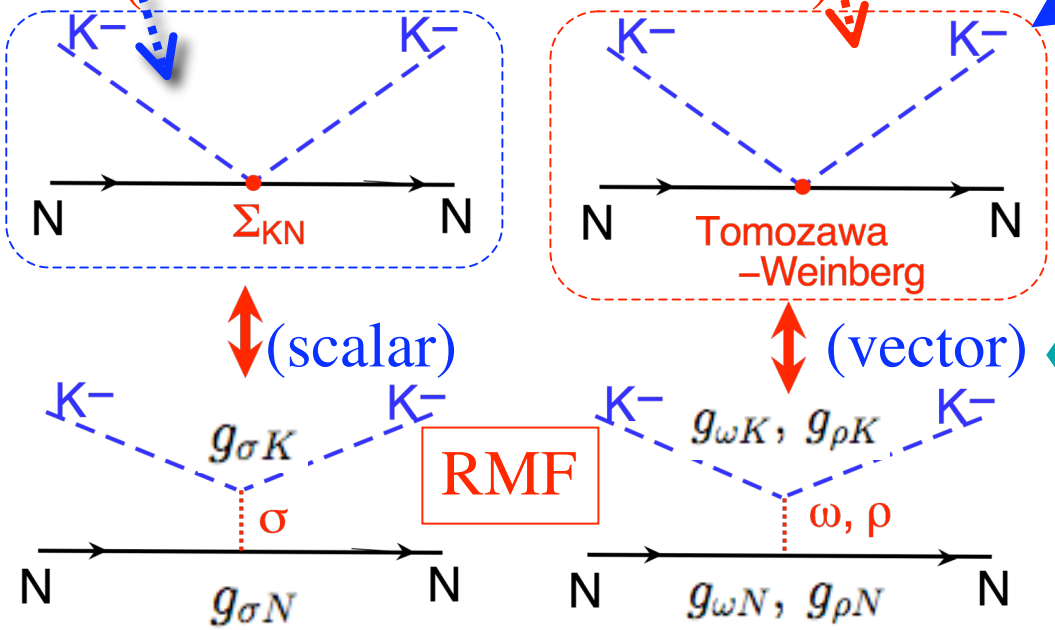
$$f = 93 \text{ MeV}$$

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 interactions)



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

(KN sigma term)

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

(Tomozawa-Weinberg)

2-4 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

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

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

range terms

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

pole term Λ(1405) (= point particle)

Effective nucleon mass

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

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

Lowest energy of K^-

$$\tilde{\omega}_{K^-} = \omega_{K^-} - V_{\text{Coul}}$$

Choice of parameters

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

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

S-wave on-shell KN scattering lengths

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

$$a(K^-p) = -0.67 + i0.64 \text{ fm}$$

$$a(K^-n) = 0.37 + i0.60 \text{ fm}$$

$$a(K^+p) = -0.33 \text{ fm} \qquad a(K^+n) = -0.16 \text{ fm}$$

2-5 Equations of motion with SOE

(coherent state)

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

K⁻ field equation

• nonlinear $\bar{K}$-$\bar{K}$ int.

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

pole term Λ(1405) (= point particle)

range terms

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

($\bar{K}\bar{K}\sigma$ scalar coupling) ($\bar{K}\bar{K}\omega(\bar{K}\bar{K}\rho)$ vector coupling)

Equations of motion for mesons and Coulomb field

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

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

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

Coulomb field: $$\nabla^2 V_{\text{Coulomb}} = 4\pi e^2\rho_{\text{ch}}$$

2-6 Choice of parameters

--- NN interaction ---

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

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

--- KN interaction ---

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

quark and isospin counting rule

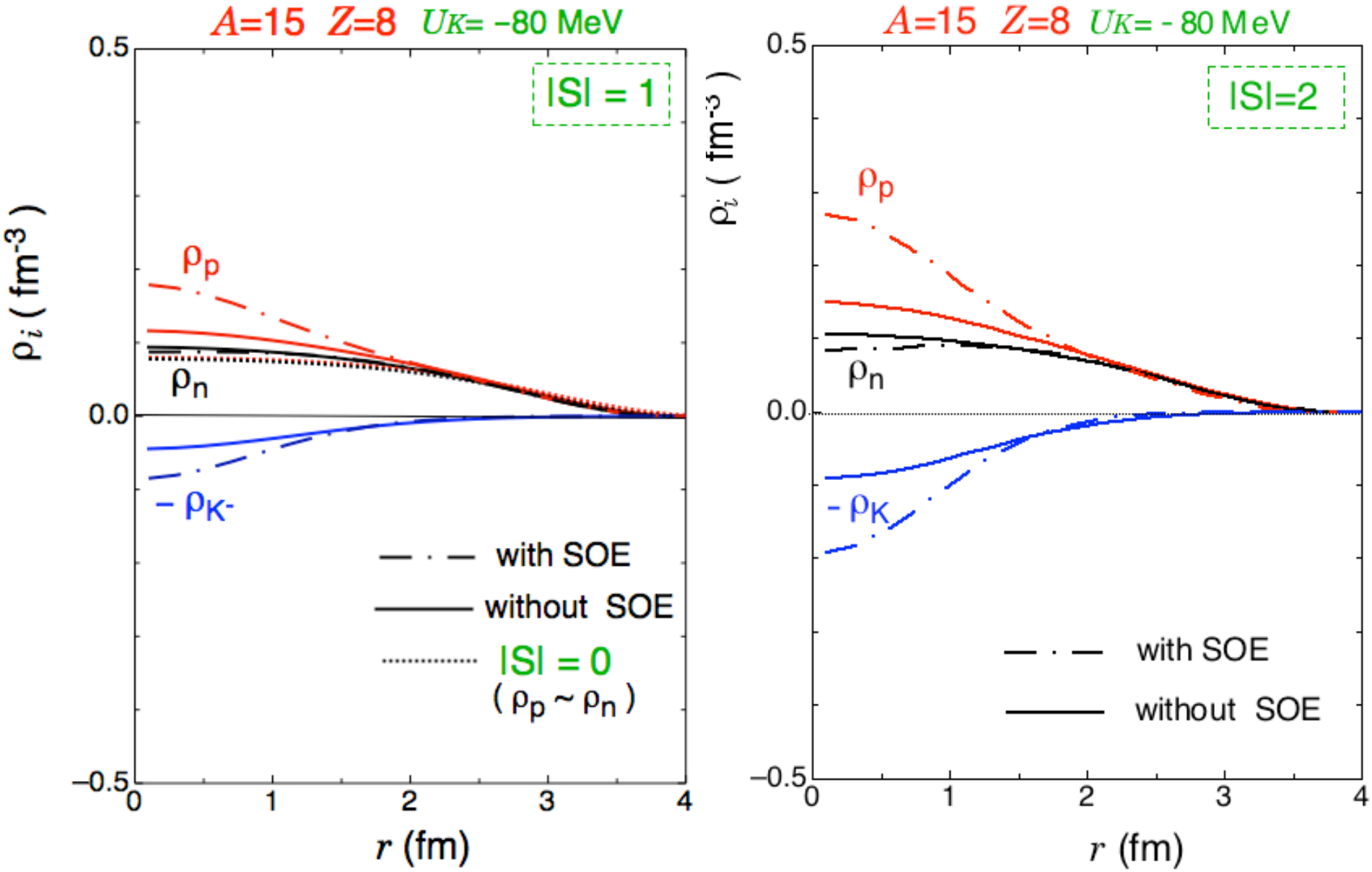
$g_{\sigma K}$

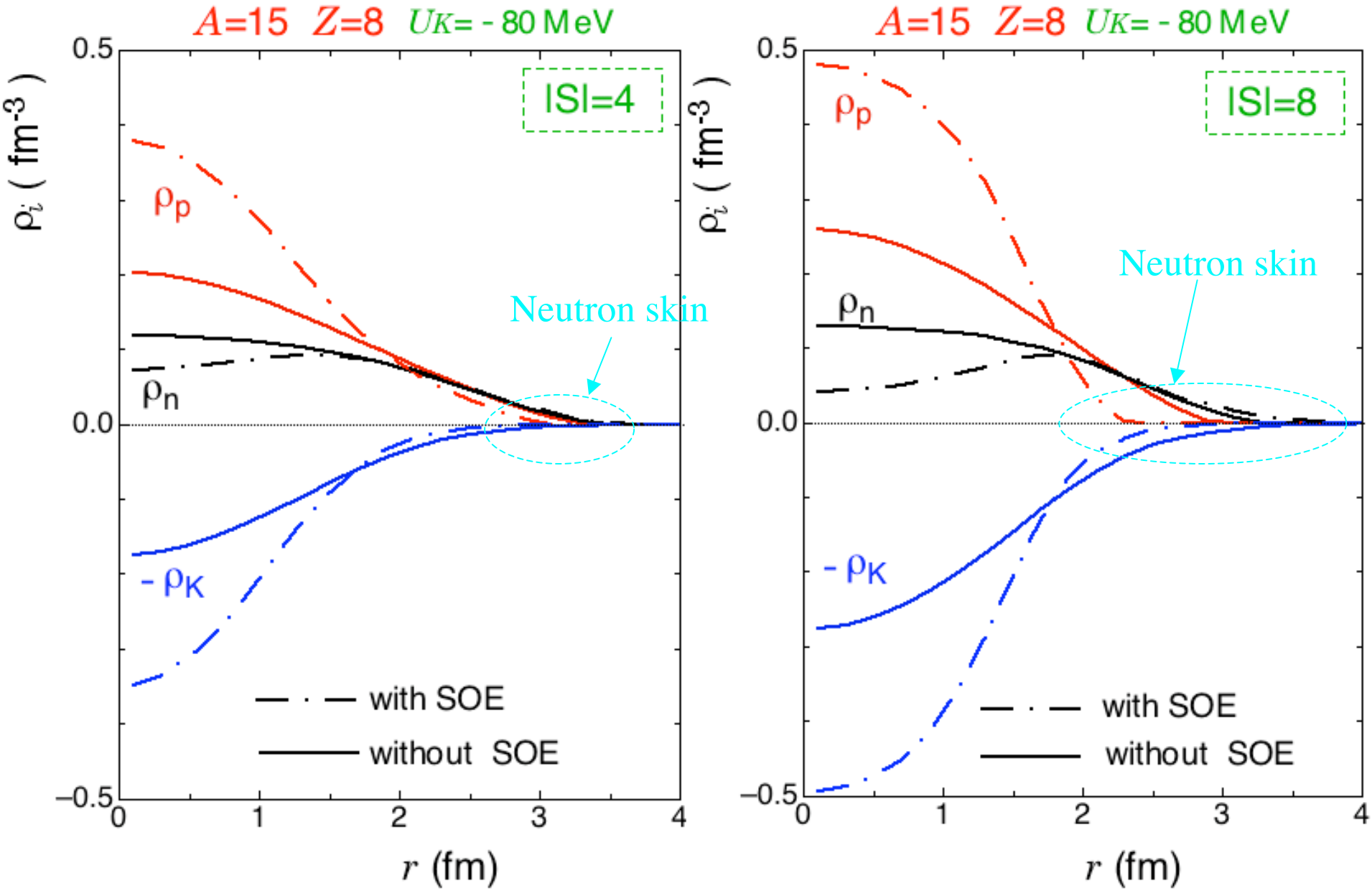
$U_K = -(g_{\sigma K}\sigma + g_{\omega K}\omega_0)$ at ρ_0 in symmetric nuclear matter

U_K= - 80 MeV (Σ_{KN} ~ 330 MeV)

3. Numerical results 3-1 Effects of range terms and Λ(1405) on density distributions

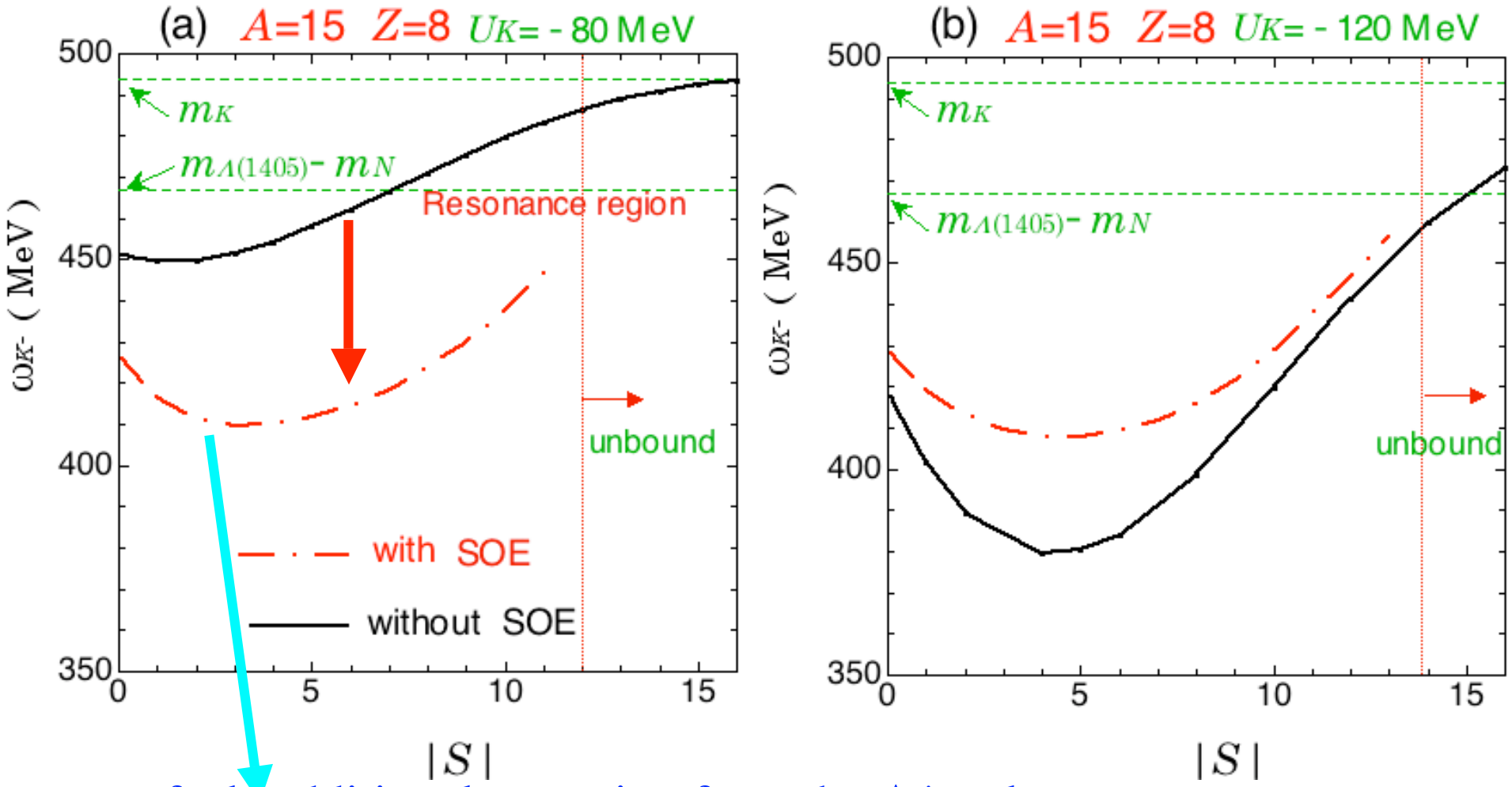
U_K= - 80 MeV





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

3-2 ground state K^- energy ω_{K^-}



- ω_{K^-} feels additional attraction from the Λ^* pole.
- With increase in |S|, ω_{K^-} increases due to the repulsive $\bar{K}$-$\bar{K}$ interaction.
- For |S| ≧ 12, K^- mesons become unbound, where $\omega_{K^-} \gtrsim m(1405) - m_N$

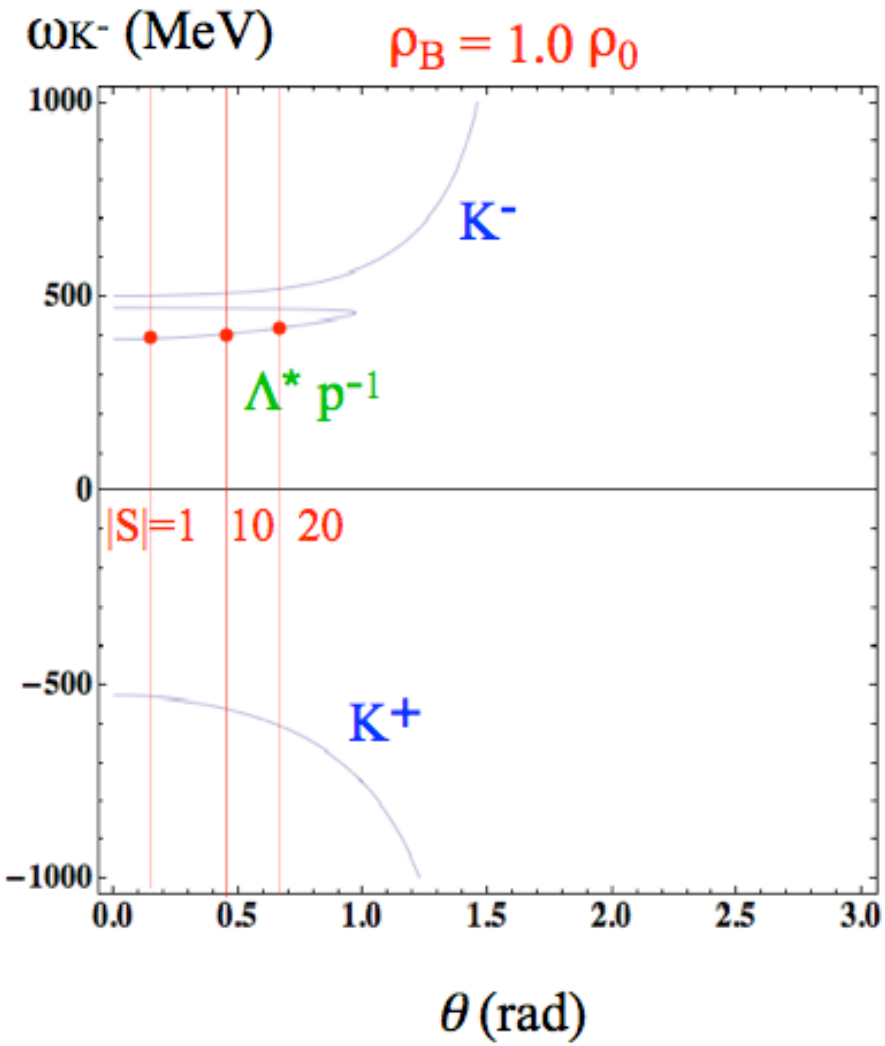
(above the Λ^* -resonance region)

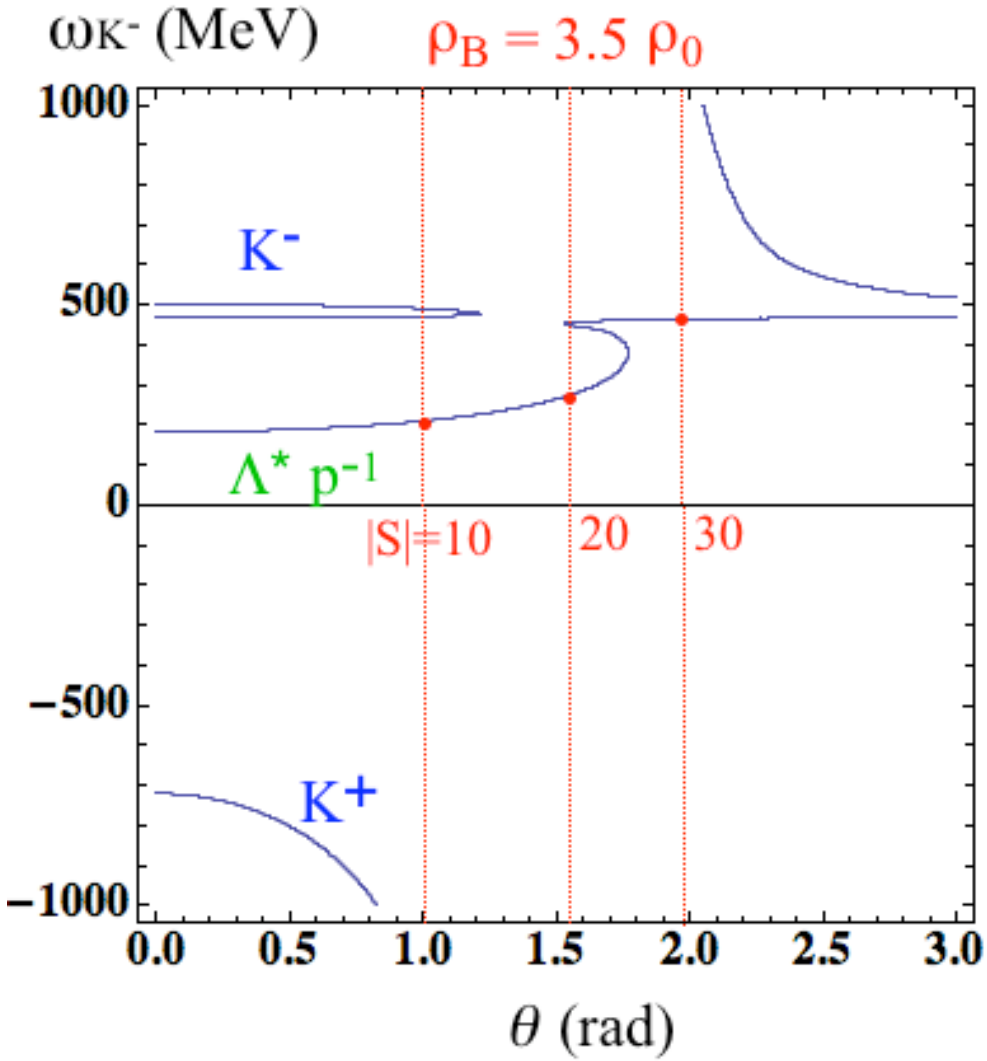
Structure of K^- and $\Lambda^* p^{-1}$ branches as functions of θ

(Neglect of finite-size effect)

$\partial\Omega/\partial\theta = 0$ → $\omega_{K^-} = \omega_{K^-}(\rho_B, \theta)$: ground-state energy of K^-

$|S|/A = \rho_{K^-} = \omega_{K^-} f^2 \sin^2\theta + \left(\rho_p + \frac{1}{2}\rho_n\right)(1 - \cos\theta)$: K^- number density





4. Implications for experiments

Outer region

Neutron-skin structure becomes more remarkable with increase in |S|.

^{15}O neutron-skin

$$\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$$

(Chiral model results)

|S|	$\sqrt{\langle r^2 \rangle_K}$ (fm)	$\sqrt{\langle r^2 \rangle_n}$ (fm)	$\sqrt{\langle r^2 \rangle_p}$ (fm)	δ_{np} (fm)
0	—	2.43	2.52	—
1	1.62	2.32	2.24	0.08
2	1.54	2.27	2.04	0.23
4	1.50	2.22	1.75	0.48
8	1.53	2.29	1.39	0.90

- information on the strength of $\bar{K} - N$ int.

δ_{np}

Observation of spin-isospin responses on the MKN

Spin dipole excitations

$$S_- - S_+ = \frac{9}{4\pi}\left(N\langle r^2 \rangle_n - Z\langle r^2 \rangle_p\right)$$

Isovector spin monopole resonances

$$S_- - S_+ = 3\left(N\langle r^4 \rangle_n - Z\langle r^4 \rangle_p\right)$$

[H. Sakai, Proc.of EXOCT07, p.345.
K. Yako, H. Sakai, H. Sagawa, ibid p.351.]

- information on Neutron-rich matter at subnuclear densities

(Symmetry energy…)

[B. A. Brown Phys. Rev. Lett.85, 5296(2000).
R. J. Furnstahl, Nucl. Phys. A 706 (2002) 85.]
[V. Rodin, Prog. Part.Nucl.Phys.59 (207) 268.]

Central region

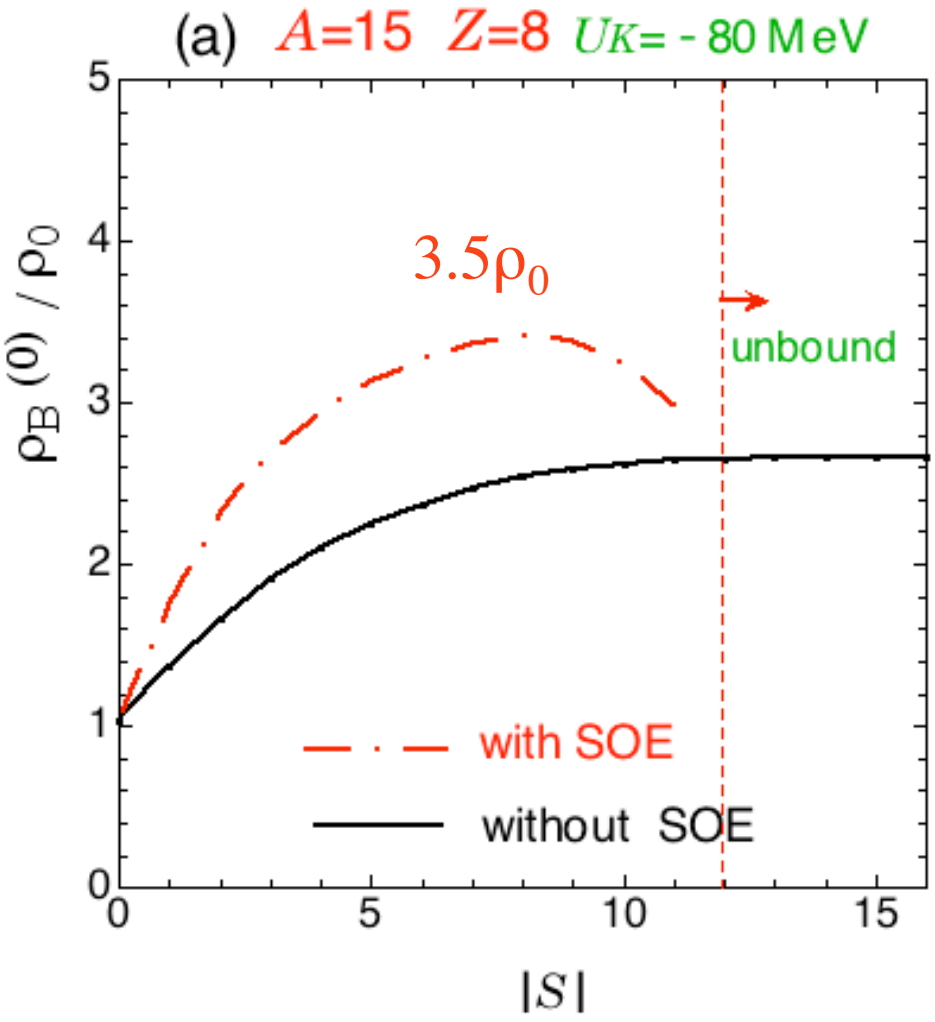
K^- mesons and protons are attracted each other around the center of the MKN.

high-density matter

Information on the $\bar{K}-N$ and $\bar{K}-\bar{K}$ interactions at high-baryon densities

baryon density $\rho_B\,(r = 0) / \rho_0$

($\rho_0 = 0.153\ \mathrm{fm}^{-3}$)



5. 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 0.5~1 fm for |S|= 4~10. remarkable for large |S|

Gross structure hardly depends on U_K.

Future problems

Interplay of K^- and $\Lambda^* p^{-1}$ branches on the structure of the MKN

Role of hyperons (Y)

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

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

- hyperon -mixing effects (coexistence of antikaons and hyperons)

  --- a possibility of more strongly bound states

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

- Fragments including K^- mesons in heavy-ion collisions
- fusion of single $\bar{K}$ nuclei