Impact of the isospin symmetry breaking on nuclear properties

内藤 智也 (Tomoya Naito)

RIKEN iTHEMS Program, JAPAN
Department of Physics, Graduate School of Science, The University of Tokyo, JAPAN

06 November 2024
SSNET'24
International Conference on Shapes and Symmetries in Nuclei: From Experiment to Theory

Laboratoire De Physique Des 2 Infinis Irène Joliot-Curie (IJCLab), Orsay, FRANCE

iTHEMS
RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

MLPhys
Foundation of "Machine Learning Physics"
学習物理学の創成

Isospin symmetry breaking of nuclear interaction

- Nuclear interaction: *almost* isospin symmetric $v_{pp}^{T=1} \simeq v_{pn}^{T=1} \simeq v_{nn}^{T=1}$

Miller, Opper, and Stephenson. *Annu. Rev. Nucl. Part. Sci.* **56**, 253 (2006)

Isospin symmetry breaking of nuclear interaction

- Nuclear interaction: *almost* isospin symmetric $v_{pp}^{T=1} \simeq v_{pn}^{T=1} \simeq v_{nn}^{T=1}$
- **Charge symmetry breaking (CSB)**
  - Difference between p-p int. and n-n int.

$$v_{\mathrm{CSB}} \equiv v_{nn}^{T=1} - v_{pp}^{T=1} \sim \tau_{zi} + \tau_{zj}$$

  - Originates from mass difference of nucleons ($m_p \neq m_n$) and π^0-η & ρ^0-ω mixings in meson-exchange process
  - Contribute to β term (β^{2n+1} terms) in nuclear EoS
- **Charge independence breaking (CIB)**
  - Difference between like-particle int. and diff.-particle int.

$$v_{\mathrm{CIB}} \equiv \frac{v_{nn}^{T=1} + v_{pp}^{T=1}}{2} - v_{np}^{T=1} \sim \tau_{zi}\tau_{zj}$$

  - Originates from mass difference of pions ($m_{\pi^0} \neq m_{\pi^\pm}$)
  - Contribute to SNM and β^2 term (β^{2n} terms) in nuclear EoS

Miller, Opper, and Stephenson. *Annu. Rev. Nucl. Part. Sci.* **56**, 253 (2006)

Introduction

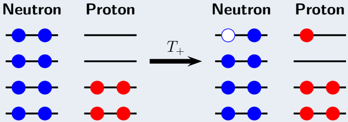
Isospin symmetry breaking of atomic nuclei

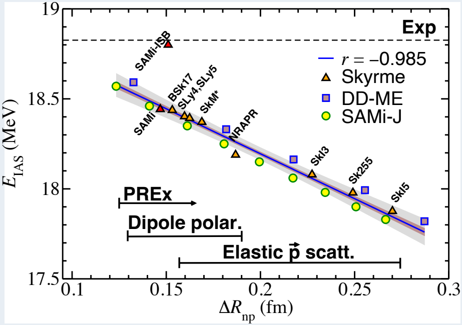
- Different properties of mirror nuclei
  - Mass (Okamoto-Nolen-Schiffer anomaly)
  - Ground-state spin ($^{73}_{38}\mathrm{Sr}$ $(5/2^{-})$ and $^{73}_{35}\mathrm{Br}$ $(1/2^{-})$ at NSCL)
    ← New result by Alejandro Algora yesterday ($^{71}\mathrm{Br}$ and $^{71}\mathrm{Kr}$ at RIBF)
  - Shape ($^{70}_{36}\mathrm{Kr}$ and $^{70}_{34}\mathrm{Se}$ at RIBF)
- Finite (negative) neutron-skin thickness $\Delta R_{np} = R_n - R_p$ of $N = Z$ nuclei

Okamoto. *Phys. Lett.* **11**, 150 (1964)
Nolen and Schiffer. *Annu. Rev. Nucl. Sci.* **19**, 471 (1969)
Hoff *et al. Nature* **580**, 52 (2020)
Wimmer *et al. Phys. Rev. Lett.* **126**, 072501 (2021)

Algora *et al.* arXiv:2411.00509 [nucl-ex]

Isobaric analog energy (IAE) and neutron-skin thickness





- Isobaric analog energy: Energy difference between $|\Psi\rangle$ and $T_\pm |\Psi\rangle$
  - E.g. ${}^{208}_{82}\mathrm{Pb}$ and ${}^{208}_{83}\mathrm{Bi}^*$
  - Spatial-spin wave function is almost the same
  - Energy difference originates from Coulomb interaction
- There is a correlation between E_{IAS} and ΔR_{np} of ${}^{208}\mathrm{Pb}$
- Exp. values of E_{IAS} and ΔR_{np} cannot be described at the same time

Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)

Skyrme-like ISB interaction

- To perform mean-field (DFT) calculation,
  the Skyrme-like ISB interaction is introduced

$$v_{\mathrm{Sky}}^{\mathrm{CSB}}(\boldsymbol{r}) = s_0 (1 + y_0 P_\sigma) \delta(\boldsymbol{r}) \frac{\tau_{1z} + \tau_{2z}}{4}$$

$$v_{\mathrm{Sky}}^{\mathrm{CIB}}(\boldsymbol{r}) = u_0 (1 + z_0 P_\sigma) \delta(\boldsymbol{r}) \frac{\tau_{1z} \tau_{2z}}{2}$$

$$\mathcal{E}_{\mathrm{CSB}} = \frac{s_0 (1 - y_0)}{8} \left(\rho_n^2 - \rho_p^2\right)$$

$$\mathcal{E}_{\mathrm{CIB}} = \frac{u_0}{8} \left[(1 - z_0) \left(\rho_n^2 + \rho_p^2\right) - 2 (2 + z_0) \rho_n \rho_p\right]$$

Note: $\tau_z = -1$ for protons and $\tau_z = +1$ for neutrons (low-energy convention)

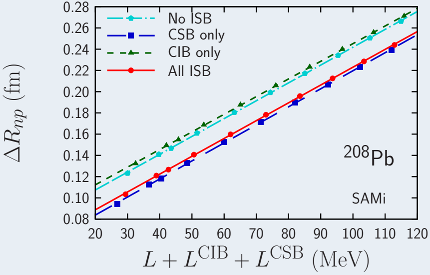
- SAMi-ISB EDF is used in this work
  - $y_0 = z_0 = -1$ to select the spin-singlet ($S = 0$) channel
  - s_0 and u_0 are parameters
  - All the parameters including the main part are optimized altoghether
- Spherical symmetry is assumed to avoid the deformation effect

Sagawa, Van Giai, and Suzuki. *Phys. Lett. B* **353**, 7 (1995)

Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)

Isospin Symmetry Breaking in Nuclear DFT

Neutron-skin thickness of $^{208}\mathrm{Pb}$



- L vs ΔR_{np} correlation is estimated using SAMi-J family
- SAMi-J fmaily
  Same as SAMi but different J
  → Different L
- On top of SAMi-J family, ISB terms are considered

- If we assume the same ΔR_{np}, difference between estimated L_{full} without & that with ISB is $11.1\,\mathrm{MeV}$

  CSB contribution $13.9\,\mathrm{MeV}$
  CIB contribution $-2.7\,\mathrm{MeV}$
- $L_{\mathrm{CIB}} = 2.3\,\mathrm{MeV}$ and $L_{\mathrm{CSB}} = -3.2\,\mathrm{MeV}$ → Change of L is $12\,\mathrm{MeV}$

Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **107**, 064302 (2023)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)
- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation

$O(10)\ \mathrm{MeV\,fm^3}$

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)
- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation
  - $s_0 \simeq -2\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$, CC & χEFT)
  - $s_0 \simeq -3\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{10}\mathrm{Be}$-$^{10}\mathrm{C}$, VMC & AV18)

$O(10)\ \mathrm{MeV\,fm^3}$

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)

$O(10)\ \mathrm{MeV\,fm^3}$

- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation
  - $s_0 \simeq -2\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$, CC & χEFT)
  - $s_0 \simeq -3\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{10}\mathrm{Be}$-$^{10}\mathrm{C}$, VMC & AV18)

$O(1)\ \mathrm{MeV\,fm^3}$

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)

$O(10)\ \mathrm{MeV\,fm^3}$

- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation
  - $s_0 \simeq -2\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$, CC & χEFT)
  - $s_0 \simeq -3\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{10}\mathrm{Be}$-$^{10}\mathrm{C}$, VMC & AV18)

$O(1)\ \mathrm{MeV\,fm^3}$

- CSB effect in *ab initio* is $\times 0.1$ of that in DFT?!?!

Open problem

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

Mysterious of CSB strength

- ISB effects on nuclear properties depends on ISB strengths
- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)

$O(10)\ \mathrm{MeV\,fm^3}$

- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation
  - $s_0 \simeq -2\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$, CC & χEFT)
  - $s_0 \simeq -3\,\mathrm{MeV\,fm^3}$ (ΔE_{tot} of $^{10}\mathrm{Be}$-$^{10}\mathrm{C}$, VMC & AV18)

$O(1)\ \mathrm{MeV\,fm^3}$

- CSB effect in *ab initio* is $\times 0.1$ of that in DFT?!?!

Open problem

- **We need to determine ISB strength microscopically!**

Method: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
s_0-value: Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)
s_0-value: Bączyk, Dobaczewski *et al. Phys. Lett. B* **778**, 178 (2018)
CC & χEFT: Novario, Lonardoni, Gandolfi, and Hagen. *Phys. Rev. Lett.* **130**, 032501 (2023)
VMC & AV18: Wiringa. Private communication

Summary: Naito, Colò, Liang, Roca-Maza, and Sagawa. *Nuovo Cim. C* **47**, 52 (2024)

QCD Sum Rule Approach for CSB EDF

Simplest Model Systems for ONS Anomaly

- The simplest model towards ONS anomaly is “SNM + p/n”
- Only the nuclear interaction is considered
- Nucleon mass in medium depends on density
  due to chiral symmetry breaking and its restoration
  $\to \Delta_{np} = M_n - M_p$ also depends on ρ
- Therefore, the energy difference except mass diff. can be regarded as “Okamoto-Nolen-Schiffer anomaly” $\Delta E = \delta - \Delta_{np}\,(\rho = 0)$

SNM
$(\rho_n = \rho_p)$

SNM
$(\rho_n = \rho_p)$

QSR Approach for Δ_{np}

- In-medium self-energy Σ_τ can be calculated by QSR

$$\Delta_{np}(\rho) = \omega_n - \omega_p \simeq \Sigma_n^{\mathrm{S}} - \Sigma_p^{\mathrm{S}}$$

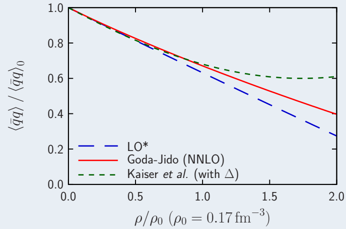
- Using the Borel sum and QSR,

$$\Delta_{np}(\rho) = C_1 \left(\frac{\langle \overline{q} q \rangle_\rho}{\langle \overline{q} q \rangle_0} \right)^{1/3} - C_2 \qquad C_1 = -a\gamma \qquad \gamma = \frac{\left\langle \overline{d} d \right\rangle_0}{\langle \overline{u} u \rangle_0} - 1$$

(ω_τ: Time-component of 4-momentum, Σ_τ^{S}: Scalar self-energy, $C_1 = 5.24^{+2.48}_{-1.21}\,\mathrm{MeV}$)

Hatsuda, Høgaasen, and Prakash. *Phys. Rev. Lett.* **66**, 2851 (1991)

Estimation of In-Medium Chiral Condensation



$$\frac{\langle \overline{q} q \rangle_\rho}{\langle \overline{q} q \rangle_0} \simeq 1 + k_1 \frac{\rho}{\rho_0} + k_2 \left(\frac{\rho}{\rho_0} \right)^{5/3}$$

$$k_1 = -\frac{\sigma_{\pi N} \rho_0}{f_\pi^2 m_\pi^2} \qquad k_2 = -k_1 \frac{3 k_{\mathrm{F}0}^2}{10 m_N^2}$$

$\sigma_{\pi N}$: π-N sigma term, f_π: pion decay const.

Goda and Jido. *Phys. Rev. C* **88**, 065204 (2013)

QCD Sum Rule Approach for CSB EDF

Estimation of Δ_{np}

- Eventually, the ONS anomaly $\delta_{\mathrm{QSR}} = \Delta_{np}(\rho = 0) - \Delta_{np}(\rho)$ is

$$\begin{aligned}
\delta_{\mathrm{QSR}} &= C_1 \left[1 - \left(\frac{\langle \overline{q} q \rangle_\rho}{\langle \overline{q} q \rangle_0} \right)^{1/3} \right] \\
&= C_1 \left[\frac{\sigma_{\pi N}}{3 f_\pi^2 m_\pi^2} \rho - \left(\frac{3\pi^2}{2} \right)^{2/3} \frac{\sigma_{\pi N}}{10 f_\pi^2 m_N^2 m_\pi^2} \rho^{5/3} + \dots \right]
\end{aligned}$$

Sagawa, Naito, Roca-Maza, and Hatsuda. *Phys. Rev. C* **109**, L011302 (2024)

QCD Sum Rule Approach for CSB EDF

Effective Interaction Approach

- We introduce Skyrme-type CSB interaction

$$v_{\mathrm{Sky}}^{\mathrm{CSB}}(\boldsymbol{r}) = \left\{ s_0 (1 + y_0 P_\sigma) \delta(\boldsymbol{r}) + \frac{s_1}{2} (1 + y_1 P_\sigma) \left[\boldsymbol{p}^{\dagger 2} \delta(\boldsymbol{r}) + \delta(\boldsymbol{r}) \boldsymbol{p}^2 \right] \right.$$

$$\left. + s_2 (1 + y_2 P_\sigma) \boldsymbol{p}^{\dagger} \cdot \delta(\boldsymbol{r}) \boldsymbol{p} \right\} \frac{\tau_{1z} + \tau_{2z}}{4}$$

- Contribution of $v_{\mathrm{Sky}}^{\mathrm{CSB}}$ to nuclear EoS is

$$\frac{E^{\mathrm{CSB}}}{A} = \left[\frac{\tilde{s}_0}{8} \rho + \frac{1}{20} \left(\frac{3\pi^2}{2} \right)^{2/3} (\tilde{s}_1 + 3\tilde{s}_2) \rho^{5/3} \right] \frac{\rho_n - \rho_p}{\rho}$$

$\tilde{s}_0 = s_0 (1 - y_0)$, $\tilde{s}_1 = s_1 (1 - y_1)$, $\tilde{s}_2 = s_1 (1 + y_2)$

- Therefore,

$$\delta_{\mathrm{Skyrme}} \simeq -\frac{\tilde{s}_0}{4} \rho - \frac{1}{10} \left(\frac{3\pi^2}{2} \right)^{2/3} (\tilde{s}_1 + 3\tilde{s}_2) \rho^{5/3}$$

since $\left(\rho_n - \rho_p \right) / \rho \simeq (N - Z) / A$

Sagawa, Naito, Roca-Maza, and Hatsuda. *Phys. Rev. C* **109**, L011302 (2024)

QCD Sum Rule Approach for CSB EDF

Comparison of δ Obtained by Two Methods

$$\delta_{\mathrm{QSR}} \simeq C_1 \left[\frac{\sigma_{\pi N}}{3 f_\pi^2 m_\pi^2} \rho - \left(\frac{3\pi^2}{2} \right)^{2/3} \frac{\sigma_{\pi N}}{10 f_\pi^2 m_N^2 m_\pi^2} \rho^{5/3} \right]$$

$$\delta_{\mathrm{Skyrme}} \simeq -\frac{\tilde{s}_0}{4} \rho - \frac{1}{10} \left(\frac{3\pi^2}{2} \right)^{2/3} (\tilde{s}_1 + 3 \tilde{s}_2) \rho^{5/3}$$

These two results should be identical; therefore

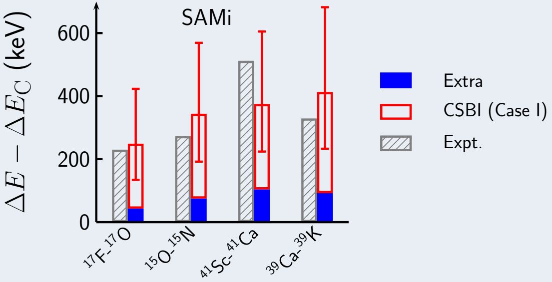
$$\begin{aligned} \tilde{s}_0 & \simeq -\frac{4}{3} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2} \\ & = -15.5^{+8.8}_{-12.5} \, \mathrm{MeV} \, \mathrm{fm}^3 \\ \tilde{s}_1 + 3 \tilde{s}_2 & \simeq \frac{1}{m_N^2} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2} \\ & = 0.52^{+0.42}_{-0.29} \, \mathrm{MeV} \, \mathrm{fm}^5 \end{aligned}$$

$\sigma_{\pi N}$ has the large uncertainty $\sigma_{\pi N} = 45 \pm 15 \, \mathrm{MeV}$ (conservative estimation)

Sagawa, Naito, Roca-Maza, and Hatsuda. *Phys. Rev. C* **109**, L011302 (2024)

QCD Sum Rule Approach for CSB EDF

Application for Actual Skyrme Hartree-Fock Calculation



- "Extra" contribution is not enough to describe ΔE
  - Higher-order correction for the Coulomb interaction
  - Change of kinetic energy due to $m_p \neq m_n$
- QCD-CSB interaction describe ΔE quite nicely
  → ONS anomaly may be solved?

Sagawa, Naito, Roca-Maza, and Hatsuda. *Phys. Rev. C* **109**, L011302 (2024)

OPEP Approach to CIB EDF

Origin of CIB interaction

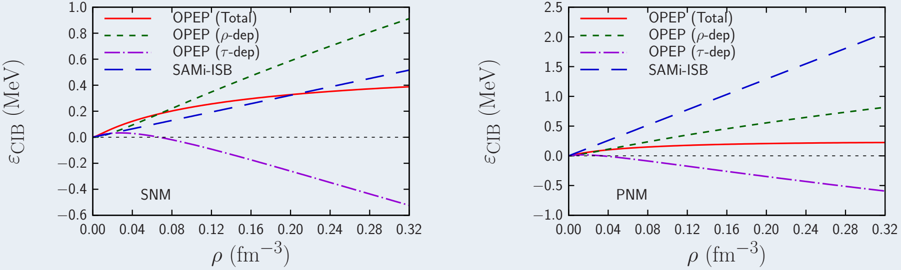
- CIB originates from $M_{\pi^0} \neq M_{\pi^\pm}$ of one-pion exchange int. (OPEP)
- OPEP up to the 2nd order of chiral expansion, OPEP is written by

$$\begin{aligned} V_{\text{OPEP}}\left(\boldsymbol{q}, pp\right) &= f^2 V\left(M_{\pi^0}, \boldsymbol{q}\right) \\ V_{\text{OPEP}}\left(\boldsymbol{q}, nn\right) &= f^2 V\left(M_{\pi^0}, \boldsymbol{q}\right) \\ V_{\text{OPEP}}\left(\boldsymbol{q}, pn\right) &= -f^2 V\left(M_{\pi^0}, \boldsymbol{q}\right) + \left(-1\right)^{T+1} 2 f^2 V\left(M_{\pi^\pm}, \boldsymbol{q}\right) \\ V\left(M_\pi, \boldsymbol{q}\right) &= -\frac{4\pi}{M_{\pi^\pm}^2} \frac{\left(\boldsymbol{\sigma}_1 \cdot \boldsymbol{q}\right)\left(\boldsymbol{\sigma}_2 \cdot \boldsymbol{q}\right)}{q^2 + M_\pi^2} \end{aligned}$$

Epelbaum and Meißner. *Phys. Rev. C* **72**, 044001 (2005)

HF calculation using OPEP

- OPEP includes spin-spin and tensor terms
  → HF exp. value of tensor term vanishes in even-even systems
- We only consider the spin-spin terms
- We calculate HF exp. value and perform density matrix expansion
- OPEP gives similar value to SAMi-ISB for SNM
- Note: In-medium effect is not included



Naito, Colò, Hatsuda, Roca-Maza, and Sagawa. *To be submitted*

Conclusion

- CSB and CIB terms contribute to
  ΔR_{np} of $^{208}\mathrm{Pb}$ in $-0.02\,\mathrm{fm}$ ($12\,\mathrm{MeV}$ in L value)
- CSB is related to chiral symmetry breaking and its restoration
- QCD sum rule approach gives CSB EDF
- OPEP & DME gives CIB EDF
  → Next step: in-medium effect
- Perspectives
  pairing, deformation, reveal the open problem, (Q)RPA calc., . . .
- Ultimate goal
  - **“Complete & accurate” nuclear EDF**
  - **Can we understand “medium effect” from QCD?**

Conclusion

- CSB and CIB terms contribute to ΔR_{np} of ${}^{208}\mathrm{Pb}$ in $-0.02\,\mathrm{fm}$ $(12\,\mathrm{MeV}$ in L value)
- CSB is related to chiral symmetry breaking and its restoration
- QCD sum rule approach gives CSB EDF
- OPEP & DME gives CIB EDF
  → Next step: in-medium effect
- Perspectives
  pairing, deformation, reveal the open problem, (Q)RPA calc., . . .
- Ultimate goal
  - **“Complete & accurate” nuclear EDF**
  - **Can we understand “medium effect” from QCD?**

Thank you for attention!!