Microscopic determination of the isospin symmetry breaking energy density functional

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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 mainly 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 mainly 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)

Isospin symmetry breaking of atomic nuclei

- Isospin symmetry of atomic nuclei is *slightly* broken due to
  - Coulomb interaction
  - Isospin symmetry breaking (ISB) terms of nuclear interaction
- Different properties of mirror nuclei
  - Mass (Okamoto-Nolen-Schiffer anomaly)
  - Ground-state spin, shape, ...
- Isobaric analog energy
- Superallowed β decay
- 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)

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Most effective interactions do not include ISB terms

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Most effective interactions do not include ISB terms
$\rightarrow$ Nuclear structure calculation with ISB terms is important
to understand these properties quantitatively

Skyrme-like ISB interaction

$$v_{\mathrm{Sky}}^{\mathrm{CSB}}(\boldsymbol{r}) = \left\{ s_0 (1 + y_0 P_\sigma) \delta(\boldsymbol{r}) + \frac{s_1}{2} (1 + y_1 P_\sigma) \left[\boldsymbol{k}^{\dagger 2} \delta(\boldsymbol{r}) + \delta(\boldsymbol{r}) \boldsymbol{k}^2 \right] + s_2 (1 + y_2 P_\sigma) \boldsymbol{k}^\dagger \cdot \delta(\boldsymbol{r}) \boldsymbol{k} \right\} \frac{\tau_{z1} + \tau_{z2}}{4}$$

$$v_{\mathrm{Sky}}^{\mathrm{CIB}}(\boldsymbol{r}) = \left\{ u_0 (1 + z_0 P_\sigma) \delta(\boldsymbol{r}) + \frac{u_1}{2} (1 + z_1 P_\sigma) \left[\boldsymbol{k}^{\dagger 2} \delta(\boldsymbol{r}) + \delta(\boldsymbol{r}) \boldsymbol{k}^2 \right] + u_2 (1 + z_2 P_\sigma) \boldsymbol{k}^\dagger \cdot \delta(\boldsymbol{r}) \boldsymbol{k} \right\} \frac{\tau_{z1} \tau_{z2}}{2}$$

$$\begin{aligned}
\mathcal{E}_{\mathrm{CSB}}^{\mathrm{H}} = {} & \frac{s_0}{4} \left(1 + \frac{y_0}{2} \right) \left(\rho_n^2 - \rho_p^2 \right) + \frac{1}{8} \left[s_1 \left(1 + \frac{y_1}{2} \right) + s_2 \left(1 + \frac{y_2}{2} \right) \right] \left(\rho_n \tau_n - \rho_p \tau_p \right) \\
& - \frac{1}{32} \left[3 s_1 \left(1 + \frac{y_1}{2} \right) - s_2 \left(1 + \frac{y_2}{2} \right) \right] \left(\rho_n \Delta \rho_n - \rho_p \Delta \rho_p \right) - \frac{1}{32} (s_1 y_1 + s_2 y_2) \left(\boldsymbol{J}_n^2 - \boldsymbol{J}_p^2 \right)
\end{aligned}$$

$$\begin{aligned}
\mathcal{E}_{\mathrm{CSB}}^{\mathrm{x}} = {} & - \frac{s_0}{4} \left(\frac{1}{2} + y_0 \right) \left(\rho_n^2 - \rho_p^2 \right) - \frac{1}{8} \left[s_1 \left(\frac{1}{2} + y_1 \right) - s_2 \left(\frac{1}{2} + y_2 \right) \right] \left(\rho_n \tau_n - \rho_p \tau_p \right) \\
& + \frac{1}{32} \left[3 s_1 \left(\frac{1}{2} + y_1 \right) + s_2 \left(\frac{1}{2} + y_2 \right) \right] \left(\rho_n \Delta \rho_n - \rho_p \Delta \rho_p \right) + \frac{1}{32} (s_1 - s_2) \left(\boldsymbol{J}_n^2 - \boldsymbol{J}_p^2 \right)
\end{aligned}$$

$$\begin{aligned}
\mathcal{E}_{\mathrm{CIB}}^{\mathrm{H}} = {} & \frac{u_0}{4} \left(1 + \frac{z_0}{2} \right) \left(\rho_n - \rho_p \right)^2 + \frac{1}{8} \left[u_1 \left(1 + \frac{z_1}{2} \right) + u_2 \left(1 + \frac{z_2}{2} \right) \right] \left(\rho_n - \rho_p \right) \left(\tau_n - \tau_p \right) \\
& - \frac{1}{32} \left[3 u_1 \left(1 + \frac{z_1}{2} \right) - u_2 \left(1 + \frac{z_2}{2} \right) \right] \left(\rho_n - \rho_p \right) \left(\Delta \rho_n - \Delta \rho_p \right) - \frac{1}{32} (u_1 z_1 + u_2 z_2) \left(\boldsymbol{J}_n - \boldsymbol{J}_p \right)^2
\end{aligned}$$

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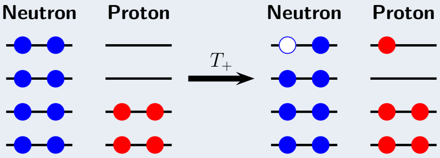
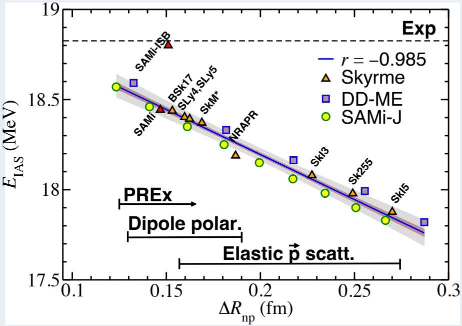
Sagawa, Colò, Roca-Maza, and Niu. *Eur. Phys. J. A* **55**, 227 (2019)

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

ISB effects on isobaric analog energy and neutron-skin thickness

Isobaric Analog State (IAS) $|\Psi_{\mathrm{IAS}}\rangle = T_{\pm}|\Psi\rangle$





- There is a correlation between E_{IAS} and ΔR_{np} of $^{208}\mathrm{Pb}$
- Without ISB terms,
  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)

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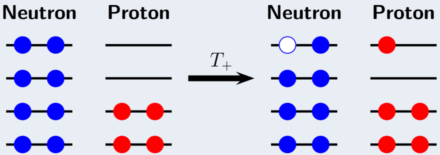

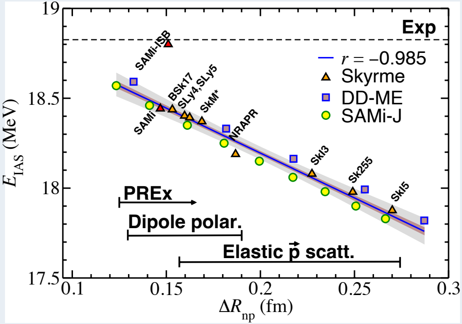

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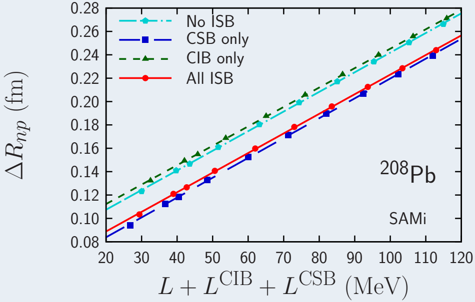
(before PREX-II data)

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

Neutron-skin thickness of ^{208}Pb and nuclear equation of state

$$\frac{E}{A} = \varepsilon_0 + \frac{K_\infty}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \ldots + \left[J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\text{sym}}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2\right]\beta^2$$



- L vs ΔR_{np} correlation estimated by SAMi-J family
- On top of SAMi-J family, ISB terms are considered
- SAMi-ISB strengths is used
  CSB $s_0 = -26.3\,\text{MeV fm}^3$
  CIB $u_0 = 25.8\,\text{MeV fm}^3$
  $y_0 = z_0 = -1$ (the others are zero)

- Difference between estimated L_{full} without & that with ISB is $11.1\,\text{MeV}$ (CSB contrib. $13.9\,\text{MeV}$, CIB contrib. $-2.7\,\text{MeV}$) → Change of L is $12\,\text{MeV}$
- Note: These values depend on the strengths of ISB terms
  →

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

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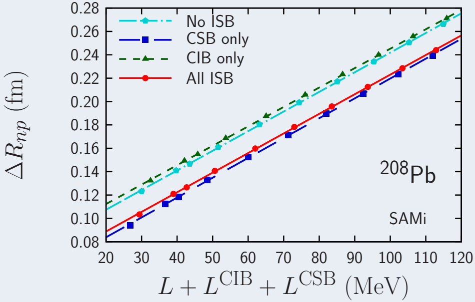

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- Note: These values depend on the strengths of ISB terms → Determination of s_j and u_j are crucial!

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

Determination of Skyrme-like CSB parameters

Here, we assume $y_0 = y_1 = -1$ and $y_2 = +1$

- Phenomenological determination $O(10)\ \mathrm{MeV\,fm^3}$
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
  - $s_0 \simeq -10\,\mathrm{MeV\,fm^3}$ (MDE and TDE)
  - $s_0 \simeq 22\,\mathrm{MeV\,fm^3}$, $s_1 \simeq -28\,\mathrm{MeV\,fm^5}$, $s_2 \simeq -16\,\mathrm{MeV\,fm^5}$ (MDE and TDE)
- Extract from *ab initio* data $O(1)\ \mathrm{MeV\,fm^3}$
  - $s_0 \simeq -2\,\mathrm{MeV\,fm^3}$ (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)

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

Isospin Symmetry Breaking of Nuclear Interaction

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→ To understand this deviation,
we attempted to determine CSB parameters using fundamental theory

QCD sum rule

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

Neutron-Skin Thickness and Charge Radii Difference

Determination from QCD sum rule

- Chiral condensation $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_0$ is related to p-n mass difference

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

obtained by QCD sum rule ($\gamma = -\left(7.8^{+3.7}_{-1.8}\right) \times 10^{-3}$, $C_1 = 5.24^{+2.48}_{-1.21}$ MeV)

- $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_0$ can be calculated by chiral perturbation theory

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \simeq 1 + k_1 \frac{\rho}{\rho_0} + k_2 \left(\frac{\rho}{\rho_0} \right)^{5/3} + \dots \qquad k_1 = -\frac{\sigma_{\pi N} \rho_0}{f_\pi^2 m_\pi^2} \qquad k_2 = -k_1 \frac{3k_{\mathrm{F0}}^2}{10 m_N^2}$$

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

Hatsuda, Høgaasen, and Prakash. *Phys. Rev. Lett.* **66**, 2851 (1991)
Goda and Jido. *Phys. Rev. C* **88**, 065204 (2013)

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

Determination from QCD sum rule

Mirror nuclei mass difference in local density approximation obtained by

- Skyrme HF calculation with s_0, s_1, and s_2
- QCD sum rule and the local density approximation

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

Neutron-Skin Thickness and Charge Radii Difference

Determination from QCD sum rule

The mass difference originating from ISB reads

$$\Delta_{\text{Skyrme}} \simeq -\frac{s_0 (1-y_0)}{4}\rho - \frac{1}{10}\left(\frac{3\pi^2}{2}\right)^{2/3} \left[s_1 (1-y_1) + 3 s_2 (1+y_2)\right] \rho^{5/3}$$

$$\Delta_{\text{QCDSR}} = C_1 \left[1 - \left(\frac{\langle \overline{q} q \rangle_\rho}{\langle \overline{q} q \rangle_0}\right)^{1/3}\right] \simeq C_1 \left\{1 - \left[1 + k_1 \frac{\rho}{\rho_0} + k_2 \left(\frac{\rho}{\rho_0}\right)^{5/3}\right]^{1/3}\right\}$$

$$\simeq C_1 \left[\frac{1}{3} \frac{\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho - \frac{1}{10}\left(\frac{3\pi^2}{2}\right)^{2/3} \frac{1}{m_N^2} \frac{\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho^{5/3}\right]$$

We obtain

$$s_0 (1-y_0) \simeq -\frac{4}{3} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2} = -15.5^{+8.8}_{-12.5}\,\text{MeV}\,\text{fm}^3$$

$$s_1 (1-y_1) + 3 s_2 (1+y_2) \simeq \frac{1}{m_N^2} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2} = 0.52^{+0.42}_{-0.29}\,\text{MeV}\,\text{fm}^5$$

(Error bar is due to $\sigma_{\pi N}$)

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

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$$\Delta_{\text{QCDSR}} = C_1\left[1-\left(\frac{\langle\overline{q}q\rangle_\rho}{\langle\overline{q}q\rangle_0}\right)^{1/3}\right] \simeq C_1\left\{1-\left[1+k_1\frac{\rho}{\rho_0}+k_2\left(\frac{\rho}{\rho_0}\right)^{5/3}\right]^{1/3}\right\}$$

$$\simeq C_1\left[\frac{1}{3}\frac{\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho - \frac{1}{10}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{1}{m_N^2}\frac{\sigma_{\pi N}}{f_\pi^2 m_\pi^2}\rho^{5/3}\right]$$

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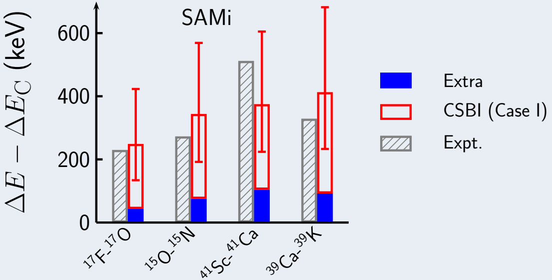
s_1 & s_2 terms may be small (Error bar is due to $\sigma_{\pi N}$)

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

ONS anomaly and QCD-CSB interaction



- "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
  $\rightarrow$ ONS anomaly may be solved?

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

Conclusion

- $O(\beta)$ term originating from CSB in EoS is related to
  - the restoration of the chiral symmetry breaking
  - effective mass (self-energy) of nucleons in medium

  → QCD sum rule approach works to understand it
- QCD-CSB interaction can describe ONS anomaly

Perspectives

- How abount CIB interaction, originating from $m_{\pi^0} \neq m_{\pi^\pm}$?
  Pion is NG boson → in-medium effect is important
- Ongoing
  - QCD-based CIB interaction (w/ Colò, Hatsuda, Roca-Maza, Sagawa)
  - Relativistic CSB EDF (w/ Cheoun, Sagawa, Tanimura)
- Ultimate goal
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  - **Can we understand "medium effect" from QCD?**

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Thank you for attention!!