Impact of the isospin symmetry breaking on the neutron-skin thickness and the nuclear equation of state

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Nuclear Interaction and Isospin T

- Nuclear interaction: isospin symmetric

  $v_{pp}^{T=1} = v_{pn}^{T=1} = v_{nn}^{T=1}$

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

Nuclear Interaction and Isospin T

- Nuclear interaction: *almost* isospin symmetric

  $$v_{pp}^{T=1} \simeq v_{pn}^{T=1} \simeq v_{nn}^{T=1}$$

- Origin of isospin symmetry breaking: $m_u \neq m_d$

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Nuclear Interaction and Isospin T

- Nuclear interaction: *almost* isospin symmetric
  $v_{pp}^{T=1} \simeq v_{pn}^{T=1} \simeq v_{nn}^{T=1}$
- Origin of isospin symmetry breaking: $m_u \neq m_d$
- **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
- **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 ($m_{\pi^0} \neq m_{\pi^\pm}$)

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

Introduction

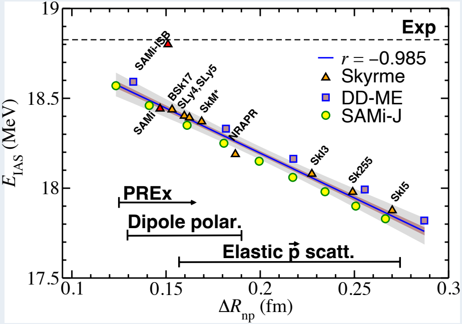
Isospin Symmetry Breaking of Atomic Nuclei

- 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
    —Coulomb int. is not enough (Okamoto-Nolen-Schiffer anomaly)
  - Ground-state spin ($^{73}_{38}\mathrm{Sr}$ $(5/2^-)$ and $^{73}_{35}\mathrm{Br}$ $(1/2^-)$ at NSCL)
  - 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)

ISB Effects on Isobaric Analog State and Neutron-Skin Thickness



- 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

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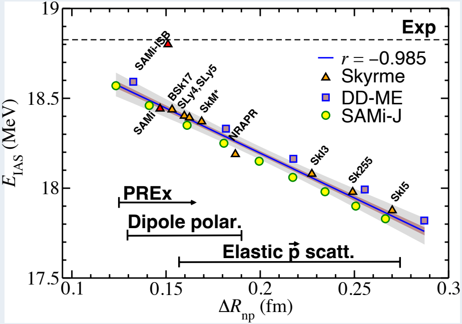

- There is a correlation between E_{IAS} and ΔR_{np} of $^{208}\mathrm{Pb}$
- Without ISB terms,
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- With ISB terms in DFT,
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Roca-Maza, Colò, and Sagawa. *Phys. Rev. Lett.* **120**, 202501 (2018)

Introduction

Current Status of ISB Interaction

- ISB terms of bare interaction: Constrained (e.g. AV18)
- Systematic study on nuclear chart → Effective int. (EDF) is needed
- Effective int. with ISB terms: Only a few
- Accuracy of effective nuclear int. (EDF)
  E_{tot} within $1\,\mathrm{MeV}$ → Final goal: $\lesssim 500\,\mathrm{keV}$? (c.f., mass model)
    - ISB terms may contribute E_{tot} in several MeV
      → ISB terms may be needed
    - Coulomb int: Not accurately treated
- Systematic study of effects of ISB terms: Not yet
    - Both ISB terms and Coulomb int. break the isospin symmetry
      → We should distinguish two contributions
    - ISB effects are not large
      → Precise calculation is needed
    - Thus, accuracy of the Coulomb EDF should be carefully considered

Series of Works

- Towards systematic studies of ISB effects on nuclear ground state, Coulomb interaction is treated precisely in nuclear DFT
  - Effect of $|\nabla\rho|$ in Coulomb exchange
  - Charge form factors of nucleons in Coulomb EDF (effects of $\rho_{\text{ch}} \not\equiv \rho_p$)
  - Vacuum polarization (e^--e^+ creation)
- Effects of ISB terms on g.s. are compared with those of Coulomb int.
  - Mass difference of mirror nuclei
  - Neutron-skin thickness of $N = Z$ and $N > Z$ nuclei
  - $\rho_{\text{IV}} = \rho_n - \rho_p$
- ISB effects on L-ΔR_{np} and L-ΔR_{ch} correlation are discussed

Naito, Akashi, and Liang. *Phys. Rev. C* **97**, 044319 (2018)
Naito, Roca-Maza, Colò, and Liang. *Phys. Rev. C* **99**, 024309 (2019)
Naito, Roca-Maza, Colò, and Liang. *Phys. Rev. C* **101**, 064311 (2020)
Sagawa, Yoshida, Naito *et al. Phys. Lett. B* **829**, 137072 (2022)
Naito, Roca-Maza, Colò, Liang, and Sagawa. *Phys. Rev. C* **106**, L061306 (2022)
Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **107**, 064302 (2023)

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Introduction

Method in This Work

- **Nuclear density functional theory (DFT)** is used
  because only this can be applied to whole nuclear chart at this moment
  $$E\left[\rho_p,\rho_n\right] = T_{\mathrm{KS}}\left[\rho_p,\rho_n\right] + E_{\mathrm{nucl}}\left[\rho_p,\rho_n\right] + E_{\mathrm{CH}}\left[\rho_{\mathrm{ch}}\right] + E_{\mathrm{Cx}}\left[\rho_{\mathrm{ch}}\right]$$
- **Skyrme-type effective interaction** is used for E_{nucl} (non-rel. calc.)

$$\begin{aligned} v^{\mathrm{IS}}_{\mathrm{Sky}}(\boldsymbol{r}) = {} & t_0\left(1 + x_0 P_\sigma\right)\delta(\boldsymbol{r}) + \frac{t_1}{2}\left(1 + x_1 P_\sigma\right)\left[\boldsymbol{p}^{\dagger 2}\delta(\boldsymbol{r}) + \delta(\boldsymbol{r})\boldsymbol{p}^2\right] + t_2\left(1 + x_2 P_\sigma\right)\boldsymbol{p}^{\dagger}\cdot\delta(\boldsymbol{r})\boldsymbol{p} \\ & + \frac{t_3}{6}\left(1 + x_3 P_\sigma\right)\delta(\boldsymbol{r})\left[\rho(\boldsymbol{R})\right]^{\alpha} + iW_0\boldsymbol{\sigma}\cdot\boldsymbol{p}^{\dagger}\times\delta(\boldsymbol{r})\boldsymbol{p} \end{aligned}$$

  SAMi and its family are used for E_{nucl}
- Doubly-magic nuclei are focused on
  → Spherical symmetry is assumed and pairing is neglected

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)

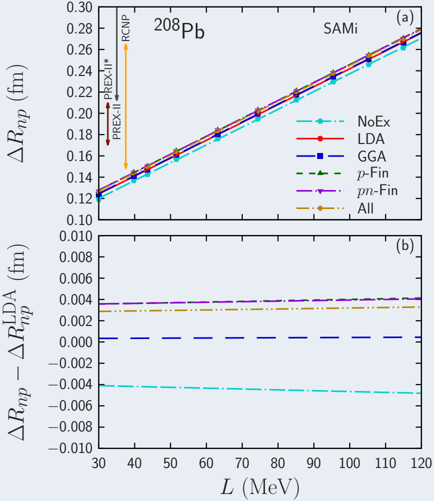
- SAMi-ISB EDF is used in this work
  - $y_0 = z_0 = -1$ to select the spin-singlet ($S = 0$) channel
  - s_0 and u_0 are parameters
  - All the parameters including the main part (t_j, x_j, W_0, W_0', α) are optimized altoghether

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

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

Neutron-Skin Thickness and Charge Radii Difference

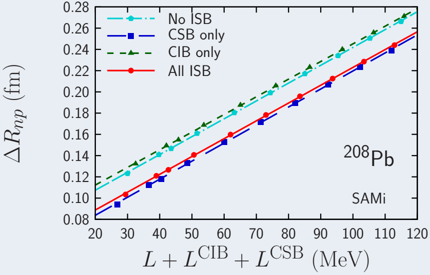
Coulomb Effect on Neutron-Skin Thickness



- ISB terms are not considered
- Treatment of Coulomb int. does not change the slope of L-ΔR_{np} dependence
- Absolute value of ΔR_{np} changes, but its value is tiny → negligible

Neutron-Skin Thickness and Charge Radii Difference

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

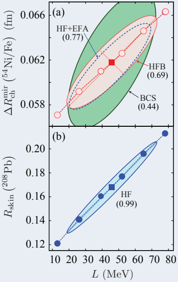
- If we assume the same ΔR_{np},
  difference between estimated L_{full} without & that with ISB is $11.1\,\mathrm{MeV}$
  CSB contribution $13.9\,\mathrm{MeV}$
  CIB contribution $-2.7\,\mathrm{MeV}$
- $L_{\mathrm{CIB}} = 2.3\,\mathrm{MeV}$ and $L_{\mathrm{CSB}} = -3.2\,\mathrm{MeV}$ → Change of L is $12\,\mathrm{MeV}$

(predicted value of L: $30 \lesssim L \lesssim 100\,\mathrm{MeV}$)

Neutron-Skin Thickness and Charge Radii Difference

Charge-Radii Difference of Mirror Nuclei

- Without Coulomb nor ISB, $R_p^{(Z,N)} = R_n^{(N,Z)}$ and $R_n^{(Z,N)} = R_p^{(N,Z)}$ hold
  $\rightarrow \Delta R_{\mathrm{ch}}^{(Z,N)} = R_{\mathrm{ch}}^{(Z,N)} - R_{\mathrm{ch}}^{(N,Z)} \simeq R_p^{(Z,N)} - R_p^{(N,Z)} = \Delta R_{np}^{(Z,N)}$
- R_{ch} can be measured precisely
- Therefore, it was proposed that ΔR_{ch} is correlated to L
- It was also pointed out that
  the correlation is weak due to pairing and deformation,
  in contrast to ΔR_{np}



Brown. *Phys. Rev. Lett.* **119**, 112502 (2017)

Reinhard and Nazarewicz. *Phys. Rev. C* **105**, L021301 (2022)

Charge-Radii Difference of Mirror Nuclei $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$

- Both $^{48}\mathrm{Ca}$ and $^{48}\mathrm{Ni}$ are doubly-magic nuclei in our calculation
  → No deformation nor pairing correlation
- Therefore, the weakly correlation problem may be avoidable

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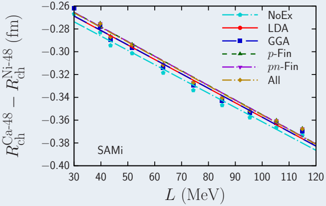

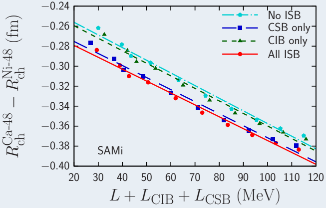

- Coulomb does not affect such correlation
- ISB terms change R_{ch}, and thus ΔR_{ch}
- If we assume the same ΔR_{ch},
  difference between estimated L_{full} without & that with ISB is $14.7\,\text{MeV}$
  (CSB: $12.7\,\text{MeV}$, CIB: $2.0\,\text{MeV}$) **Non-negligible**

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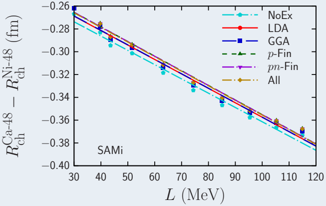

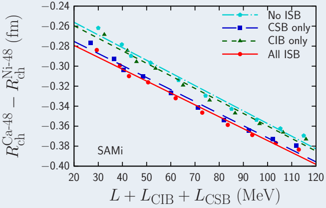

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  (CSB: $12.7\,\mathrm{MeV}$, CIB: $2.0\,\mathrm{MeV}$) **Non-negligible**
- Future perspectives: more realistic pair of mirror nuclei (e.g., $^{36}\mathrm{S}$-$^{36}\mathrm{Ca}$)

Mysterious of CSB Strength

- **Phenomenological determination**—Referring experimental data
- ***Ab initio* determination**
  —CSB strength s_0 extracted from *ab initio* calculation

Naito, Colò, Liang, Roca-Maza, and Sagawa. *Phys. Rev. C* **105**, L021304 (2022)
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VMC & AV18: Wiringa. Private communication

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- **Phenomenological determination**—Referring experimental data
  - $s_0 = -26.3\,\mathrm{MeV\,fm^3}$ (IAE of $^{208}\mathrm{Pb}$)
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$O\,(10)\ \mathrm{MeV\,fm^3}$

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

$^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$	Convergence of χEFT?
$^{10}\mathrm{Be}$-$^{10}\mathrm{C}$	Deformation? Too light?
DFT Side	s_1 & s_2 terms?

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Open problem

$^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$ Convergence of χEFT?

$^{10}\mathrm{Be}$-$^{10}\mathrm{C}$ Deformation? Too light?

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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
- $\langle \bar{q} q \rangle / \langle \bar{q} q \rangle_0$ can be calculated by using QCD sum rule
- Comparing mirror nuclei mass difference obtained by
  - Skyrme HF calculation with s_0, s_1, and s_2
  - QCD sum rule and the local density approximation

we obtain

$$\begin{aligned} s_0 &= -7.8^{+4.4}_{-6.3}\,\mathrm{MeV\,fm^3} \\ s_1 (1 - y_1) + 3 s_2 (1 + y_2) &= 0.52^{+0.42}_{-0.29}\,\mathrm{MeV\,fm^5} \end{aligned}$$

Sagawa, Naito, Roca-Maza, Hatsuda. arXiv:2305.17481 [nucl-th]

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$$s_1 (1 - y_1) + 3 s_2 (1 + y_2) = 0.52^{+0.42}_{-0.29} \, \mathrm{MeV \, fm^5}$$

s_1 & s_2 terms may be small

Sagawa, Naito, Roca-Maza, Hatsuda. arXiv:2305.17481 [nucl-th]

Conclusion

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- CSB and CIB terms contribute to ΔR_{np} of $^{208}\mathrm{Pb}$ in $-0.02\,\mathrm{fm}$
  this corresponds to $12\,\mathrm{MeV}$ in L value
- CSB and CIB terms contribute to ΔR_{ch} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$ in $-0.02\,\mathrm{fm}$
  this corresponds to $14\,\mathrm{MeV}$ in L value
- CSB effects on ΔE_{tot} in *ab initio* calculation is
  about $\times 0.1$ of that in DFT **Open problem**
- QCD sum rule approach gives $\times 1/2$–$1/3$ of DFT value
- Perspectives:
  pairing, deformation, reveal the open problem, (Q)RPA calc., …

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- CSB and CIB terms contribute to ΔR_{np} of $^{208}\mathrm{Pb}$ in $-0.02\,\mathrm{fm}$
  this corresponds to $12\,\mathrm{MeV}$ in L value
- CSB and CIB terms contribute to ΔR_{ch} of $^{48}\mathrm{Ca}$-$^{48}\mathrm{Ni}$ in $-0.02\,\mathrm{fm}$
  this corresponds to $14\,\mathrm{MeV}$ in L value
- CSB effects on ΔE_{tot} in *ab initio* calculation is
  about $\times 0.1$ of that in DFT **Open problem**
- QCD sum rule approach gives $\times 1/2$–$1/3$ of DFT value
- Perspectives:
  pairing, deformation, reveal the open problem, (Q)RPA calc., …

Grazie Mille!!