QCD-based Charge Symmetry Breaking (CSB) Interaction

Hiroyuki Sagawa   RIKEN/University of Aizu

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Isospin is one of the most important symmetries which is unique for nuclear and elementary particle physics.

Concept of Isospin proposed by J. Heisenberg, 1932 and E. P. Wigner, 1937

Isospin Breaking Interactions (ISB)

Isospin conservation $[H,T]=0$

$$[H,T]=[V_C+V_{CSB}+V_{CIB},T]\neq 0$$

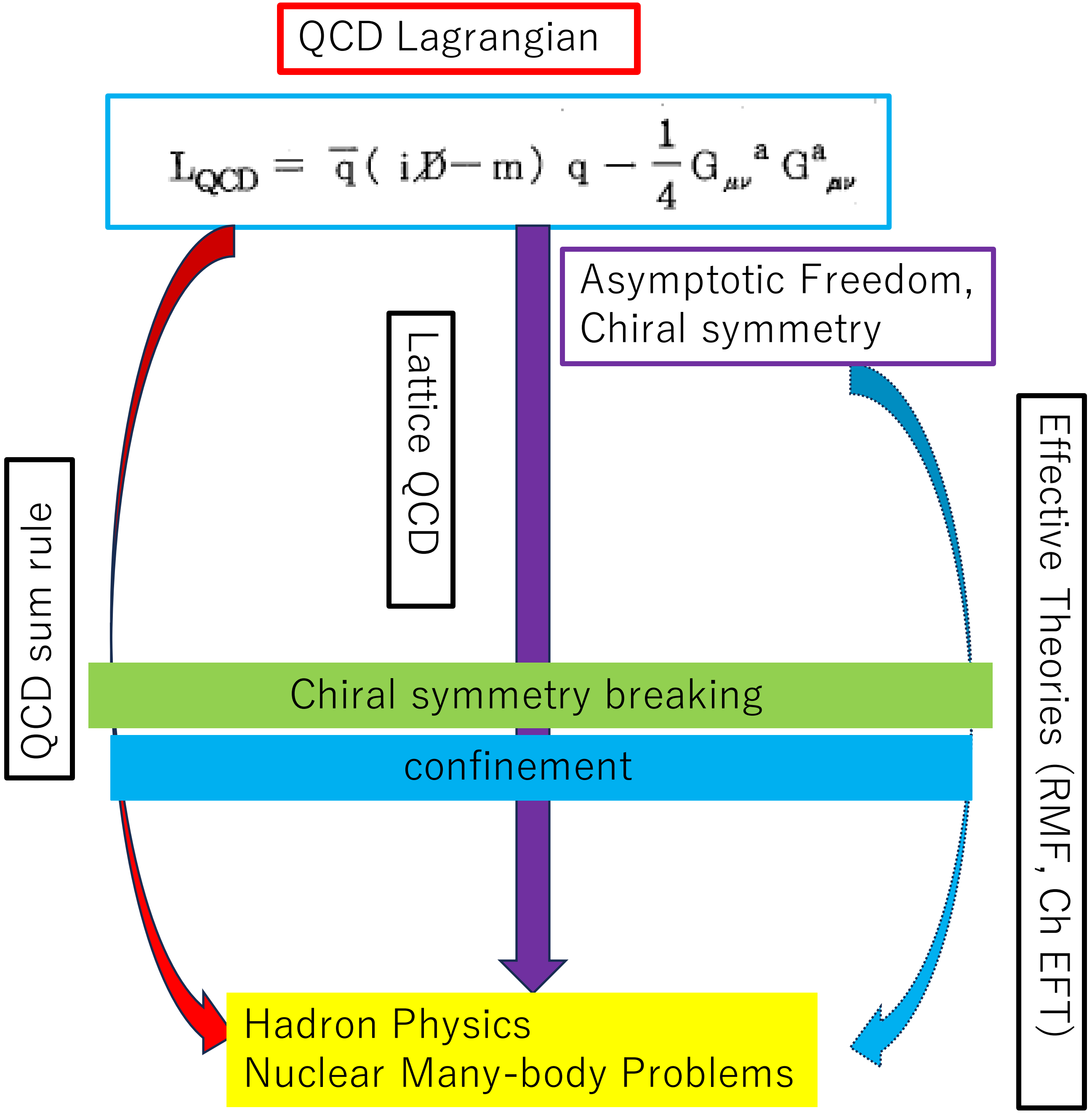
charge symmetry breaking
$V_{CSB}=V_{nn}-V_{pp}$

Charge independence breaking
$V_{CIS}=(V_{nn}+V_{pp})/2-V_{np}$

Scattering Length

$$a^{pp}_{(S=0)}=-17.3\pm0.4\text{fm},$$
$$a^{nn}_{(S=0)}=-18.7\pm0.6\text{fm},$$
$$a^{pn}_{(S=0)}=-23.70\pm0.03\text{fm}.$$

The difference between a_0^{pp} and a_0^{nn} is an evidence of CSB (charge s try breaking) nuclear force, while the difference between a_0^{pn} and the average $(a_0^{pp}+a_0^{nn})/2$ is due to CIB (charge invariance breaking) force. These negative



LQCD
⇔
ab initio no core shell model

Quark Effective theories
(**Nambu–Jona-Lasinio model**)
⇔
BCS/HF in nuclear physics

QCD sum rule
⇔
Energy weighted sum rule for
Giant resonances (RPA)

Based on a slide of T. Hatsuda

QCDの Lagrangian

$$L_{QCD} = \bar{q}(i\not{D} - m)q - \frac{1}{4} G_{\mu\nu}{}^{a} G^{a}{}_{\mu\nu}$$

HADRON PROPERTIES FROM QCD SUM RULES

L.J. REINDERS*, H. RUBINSTEIN** and S. YAZAKI***

PHYSICS REPORTS (Review Section of Physics Letters) 127, No. 1 (1985) 1–97.

Operator product expansion with nucleon current

$$\eta_N = \varepsilon_{abc}(u^a(x)C\gamma_\mu u^b(x))\gamma_5\gamma_\mu d^c(x),$$

$$\Pi_N(p) = i\int d^4x\, e^{ipx} \langle T(\eta_N(x)\, \eta_N(0))\rangle = \not{p}A(p) + B(p)$$

Operator product expansion (OPE) method

$$A(p) = \frac{1}{64\pi^2} p^4 \ln(-p^2) + \frac{1}{32\pi^2} \langle \frac{\alpha_s}{\pi} G^2 \rangle \ln(-p^2) + \frac{2}{3} \frac{\langle \bar{q}q \rangle^2}{p^2} + \cdots$$

$$B(p) = -\frac{1}{4\pi^2} \langle \bar{q}q \rangle p^2 \ln(-p^2) + \cdots$$

Phenomenological hadron propagator

$$i\int d^4x\, e^{ipx} \langle T(\eta_N(x)\, \bar{\eta}_N(0))\rangle = \lambda_N^2 \frac{\not{p} + m_N}{p^2 - m_N^2} + \text{higher states}$$

$$\eta_N(x) \equiv \lambda_N N(x)$$

Derivatives after Borel transformation

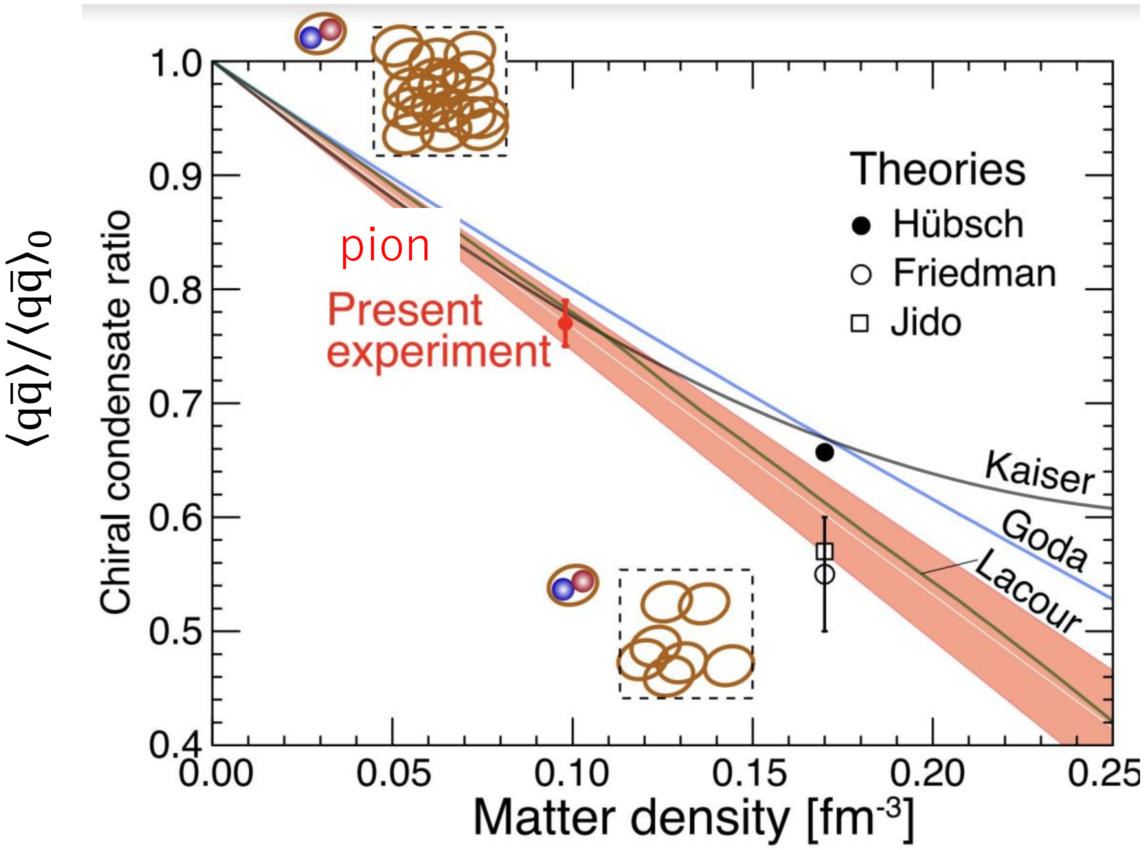
$$m_N = F(\langle \bar{q}q \rangle)$$

$$m_N = \{-2(2\pi)^2 \langle \bar{q}q \rangle\}^{1/3}$$

~1GeV

QCD-based CSB interaction

HS, T. Naito, X. Roca-Maza and T. Hatsuda, PRC109, L011302 (2024)



The in-medium chiral condensate has a general form in the leading order of Fermi motion corrections;

Goda and Jido

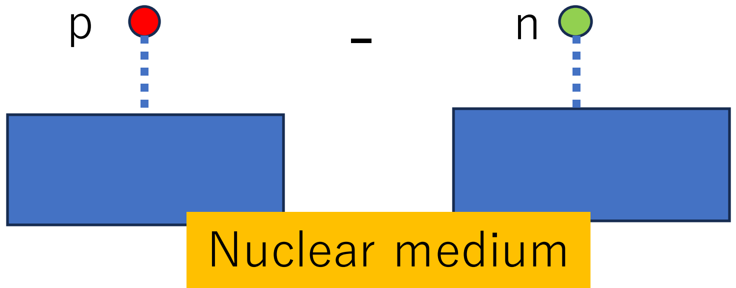
$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0} \simeq 1 + k_1 \frac{\rho}{\rho_0} + k_2 \left(\frac{\rho}{\rho_0}\right)^{5/3}, \tag{2a}$$

$$k_1 = -\frac{\sigma_{\pi N}\rho_0}{f_\pi^2 m_\pi^2} < 0, \qquad k_2 = -k_1 \frac{3k_{F0}^2}{10 m_N^2} > 0, \tag{2b}$$

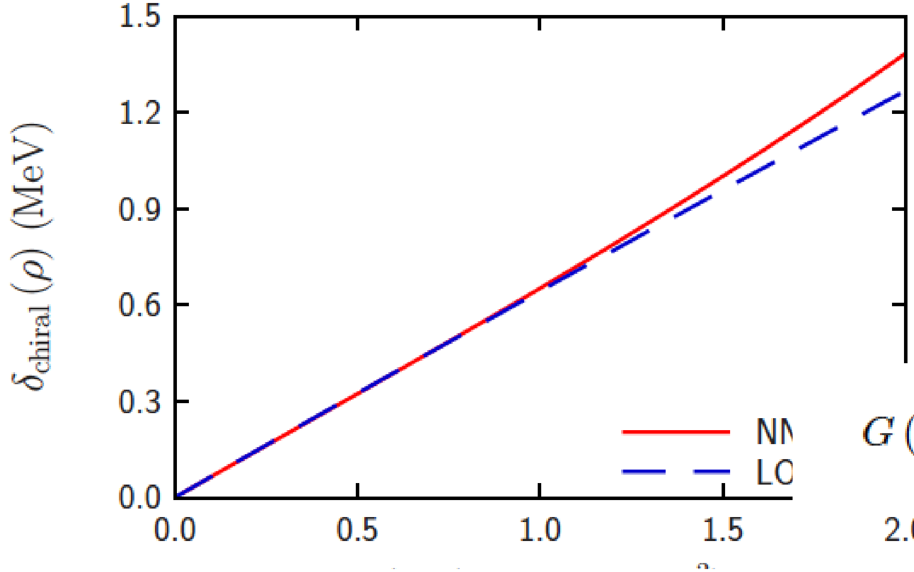
where $\sigma_{\pi N}$ is the π-N sigma term, m_π (m_N) is the pion (nucleon) mass, and f_π is the pion decay constant. The

Partial restoration of Chiral condensation of quark pairs $\bar{q}\,q$

T. Nishi et al., Nature Physics, March 23, 2023
Pionic atom experiments



The mass difference between (Z+/-1,N) and (Z, N+/-1) with N=Z



$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0} \simeq 1 + k_1 \frac{\rho}{\rho_0} + k_2 \left(\frac{\rho}{\rho_0} \right)^{5/3}, \quad \text{(2a)}$$

$$k_1 = -\frac{\sigma_{\pi N} \rho_0}{f_\pi^2 m_\pi^2} < 0, \qquad k_2 = -k_1 \frac{3k_{F0}^2}{10 m_N^2} > 0, \quad \text{(2b)}$$

where $\sigma_{\pi N}$ is the π-N sigma term, m_π (m_N) is the pion (nucleon) mass, and f_π is the pion decay constant. The

$$\tilde{s}_0 = -\frac{4}{3} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2}, \qquad \tilde{s}_1 + 3\tilde{s}_2 = \frac{1}{m_N^2} \frac{C_1 \sigma_{\pi N}}{f_\pi^2 m_\pi^2}.$$

$$G(\rho) = \left(\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0} \right)^{1/3}.$$

The Skyrme-type CSB and CIB interactions

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

$$\frac{E}{A} \simeq \varepsilon_0(\rho) + \varepsilon_1(\rho) \beta + \varepsilon_2(\rho) \beta^2.$$

$$\beta = (N - Z)/A$$

$$\Delta E = -2\varepsilon_1(\rho)$$

$$\delta_{\mathrm{Skyrme}} = -\frac{\tilde{s}_0}{4} \rho - \frac{1}{10} \left(\frac{3\pi^2}{2} \right)^{2/3} (\tilde{s}_1 + 3\tilde{s}_2) \rho^{5/3}, \quad (7)$$

where we have defined the effective coupling strengths,

$$\tilde{s}_0 \equiv s_0 (1 - y_0), \quad \tilde{s}_1 \equiv s_1 (1 - y_1), \quad \tilde{s}_2 \equiv s_2 (1 + y_2). \quad (8)$$

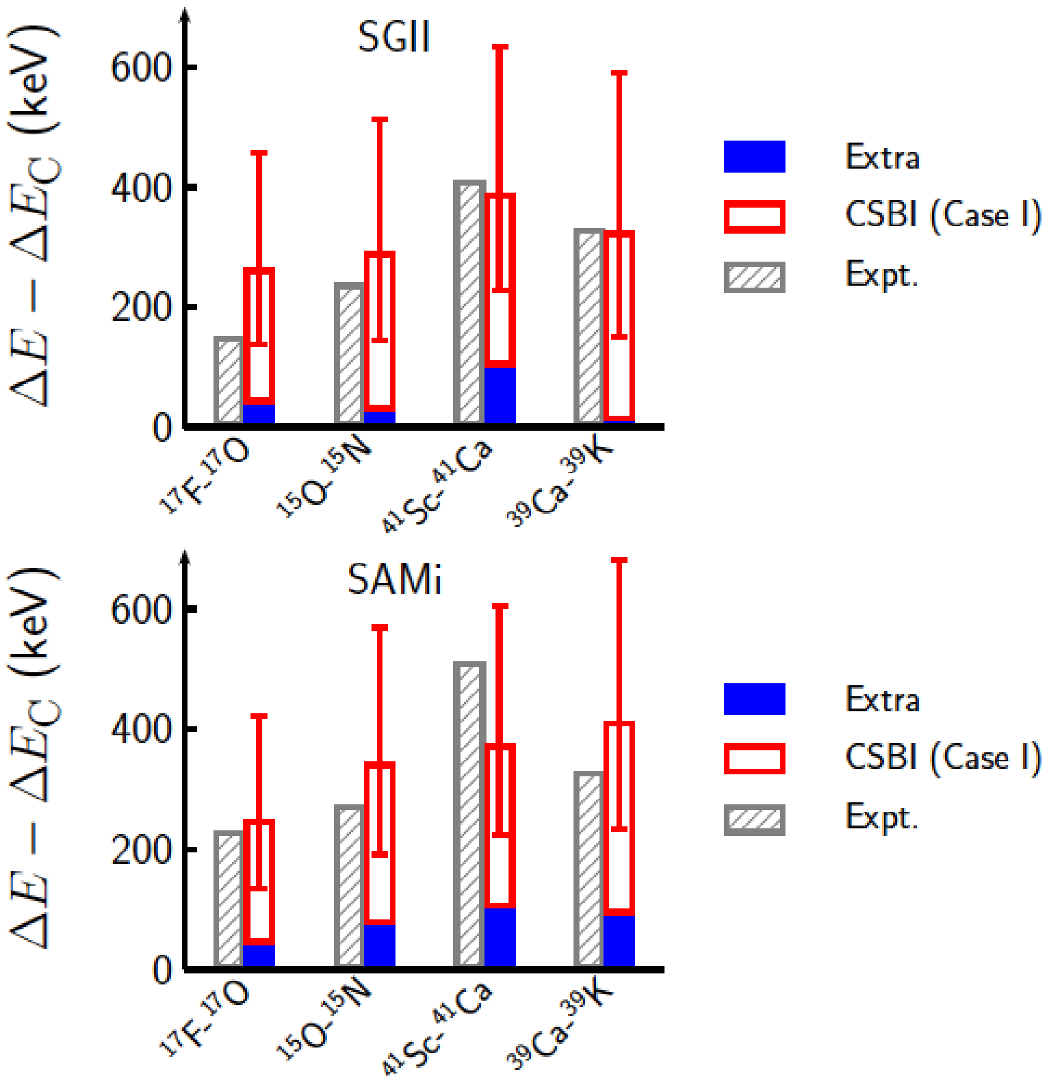


FIG. 2. Comparisons of the experimental ONS anomaly $\Delta E_{\mathrm{Expt.}} - \Delta E_{\mathrm{C}}$ (grey hatched bars) and the corresponding theoretical estimates in two EDFs (SGII and SAMi). The contribution from the QCD-based CSB interaction (CSBI) in Case I and the extra contributions are indicated by the red bars with error bars and the blue bars, respectively.

TABLE V. The breakdown of the mass difference of mirror nuclei ΔE into each contribution (Coulomb, Extra and CSB interaction (CSBI) for Case I with Skyrme EDF, SGII. Numbers are given in the unit of MeV.

Nuclei	^{17}F-^{17}O	^{15}O-^{15}N	^{41}Sc-^{41}Ca	^{39}Ca-^{39}K
Orbital	$1d_{5/2}$	$(1p_{1/2})^{-1}$	$1f_{7/2}$	$(1d_{3/2})^{-1}$
ΔE_{D} (Coulomb)	3.596	3.272	7.133	6.717
ΔE_{E} (Coulomb)	−0.203	0.026	−0.267	0.260
Extra	0.040	0.028	0.102	0.011
CSBI (Case I)	0.224	0.264	0.287	0.315
Sum (w/o CSBI)	3.432	3.326	6.965	6.985
Sum (w/ CSBI)	3.656	3.590	7.252	7.300
Expt. [29]	3.543	3.537	7.278	7.307

TABLE VI. The same as Table V, but with Skyrme EDF, SAMi.

Nuclei	^{17}F-^{17}O	^{15}O-^{15}N	^{41}Sc-^{41}Ca	^{39}Ca-^{39}K
Orbital	$1d_{5/2}$	$(1p_{1/2})^{-1}$	$1f_{7/2}$	$(1d_{3/2})^{-1}$
ΔE_{D} (Coulomb)	3.506	3.242	7.025	6.697
ΔE_{E} (Coulomb)	−0.193	0.022	−0.259	0.281
Extra	0.043	0.075	0.104	0.092
CSBI (Case I)	0.206	0.269	0.271	0.321
Sum (w/o CSBI)	3.356	3.339	6.870	7.070
Sum (w/ CSBI)	3.562	3.608	7.141	7.391
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Summary

QCD sum rule approach is adopted to obtain EDF CSB parameters without introducing any free parameters;
all QCD parameters are determined by experimental observables.

QCD-based CSB interactions are applied to solve ONS anomaly of A=16+/-1 and 40+/-1 mirror nuclei and cured all experimental observed values within the theoretical uncertainties.

Empirical evidence of CSB in hypernuclei is pointed out by RMF calculations.

Future perspectives

CIB interaction in nuclear medium
QCD based $\Lambda - N$ CSB interaction for hypernuclei

CSB and CIB effects of Isobaric Analogue states
CSB in Exotic nuclei near proton drip lines

Collaborators

Skyrme CSB,QCD-CSB

T. Naito, iTHEMS, RIKEN
T. Hatsuda, iTHEMS, RIKEN
Xavi Roca-Maza, INFN, University of Milano, Italy
Gianluca Colo, INFN, University of Milano, Italy

Hypernuclei

E Hiyama, RIKEN/Tohoku University
T.T. Sun, Zhengzhou University, China
Y. Tanimura, OMEG, Soongsil University, Korea

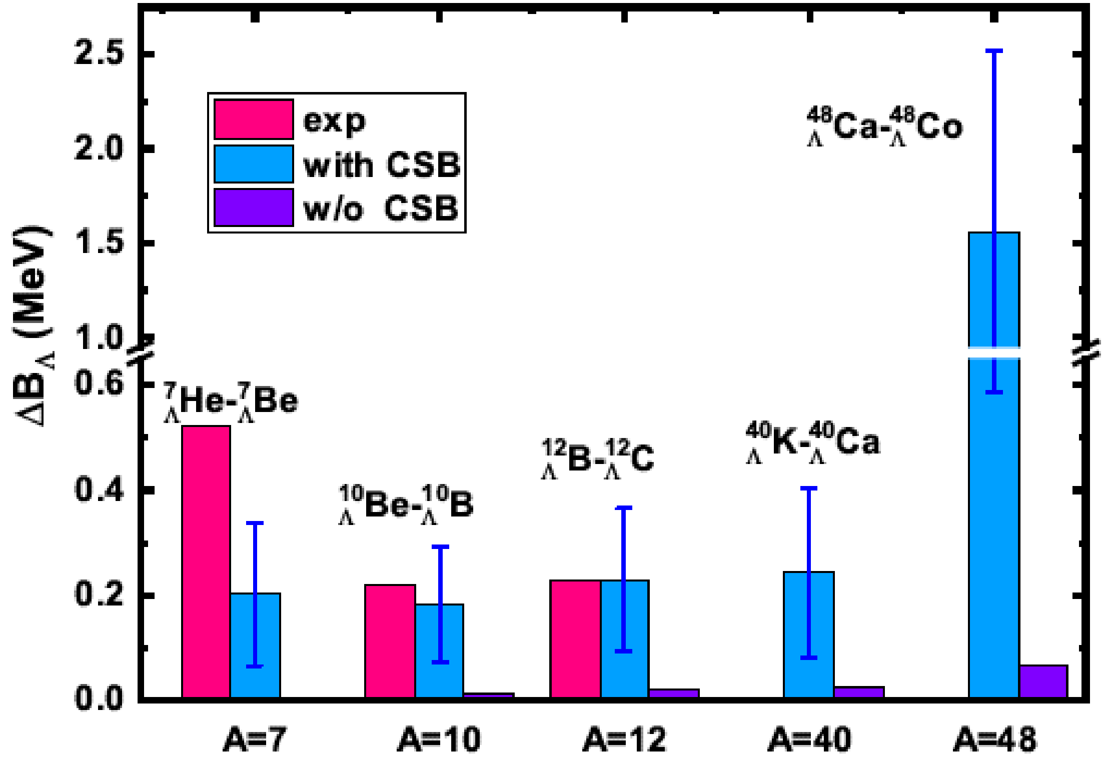

Figure 1: The differences of the single-Λ binding energy ΔB_Λ between the mirror hypernuclei ($^7_\Lambda$He, $^7_\Lambda$Be), ($^{10}_\Lambda$Be, $^{10}_\Lambda$B), ($^{12}_\Lambda$B, $^{12}_\Lambda$C), and ($^{40}_\Lambda$K, $^{40}_\Lambda$Ca), obtained by the RMF model with and without the Λ*N* charge symmetry breaking (CSB) interaction, in comparison with the experimental data.

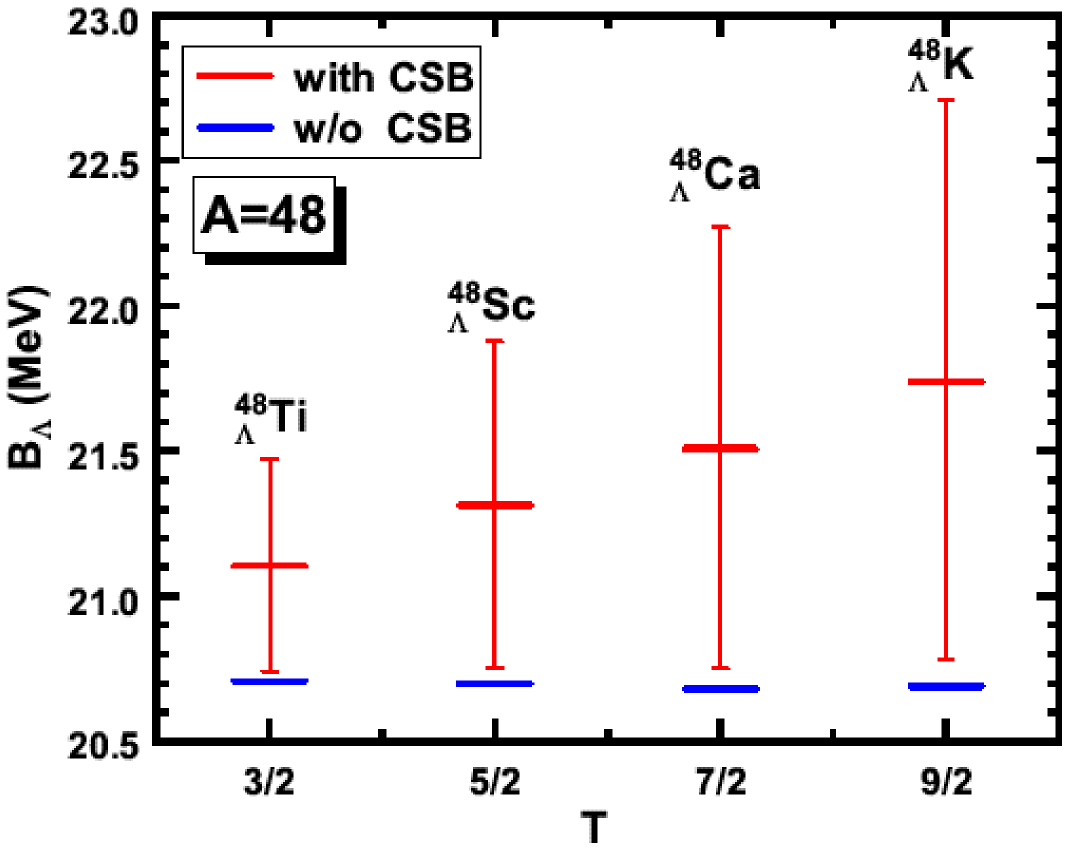

Figure 5: The single-Λ binding energies B_Λ for the $A = 48$ hypernuclei, i.e., $^{48}_\Lambda$Ti, $^{48}_\Lambda$Sc, $^{48}_\Lambda$Ca, $^{48}_\Lambda$K with isospin $T = 3/2, 5/2, 7/2, 9/2$, obtained by the RMF model with and without Λ*N* CSB interaction.

J-PARK and Jefferson Labs
Future experiments

Isospin Breaking Strong interactions

Coulomb interaction

Skyrme type ISB interactions

Charge symmetry breaking (CSB) interaction

$V_{nn} \neq V_{pp}$

$$v^{\mathrm{CSB}}_{\mathrm{Sky}}(\vec{r}) = s_0 (1 + y_0 P_\sigma)\, \delta(\vec{r})\, \frac{\tau_{z1} + \tau_{z2}}{4},$$

$$v^{\mathrm{CIB}}_{\mathrm{Sky}}(\vec{r}) = u_0 (1 + z_0 P_\sigma)\, \delta(\vec{r})\, \frac{\tau_{z1}\tau_{z2}}{2}.$$

Charge Independence breaking (CIB) interaction

$V_{np} \neq (V_{nn} + V_{pp})/2$

Hadrons: Nucleon and Pion mass difference

m_n-m_p=1.29MeV. $\pi^{\pm}$-π^{0}=4.6MeV

Quarks: explicit chiral symmetry breaking

$m_u \neq m_d$

Energy density functionals

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

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

Observables

Nolen-Schiffer anomaly
Energy of IAS
mass differences in isobar and isotriplet nuclei

SGII

Nuclei	^{17}F-^{17}O	^{15}O-^{15}N	^{41}Sc-^{41}Ca	^{39}Ca-^{39}K
Particle (hole)	$1d_{5/2}$	$(1p_{1/2})^{-1}$	$1f_{7/2}$	$(1d_{3/2})^{-1}$
Finite size	−0.053	−0.070	−0.066	−0.082
Center-of-mass	0.023	0.030	0.014	0.018
$\delta^1_{\rm NN}$	0.014	0.006	0.034	0.021
$\delta^2_{\rm NN}$	0.050	−0.136	0.134	−0.176
Spin-orbit	−0.065	0.080	−0.126	0.142
pn mass difference	0.034	0.024	0.040	0.031
$\delta_{\rm pol}$	0.018	0.073	0.036	0.020
Vacuum polarization	0.019	0.021	0.036	0.037
Sum	0.040	0.028	0.102	0.011

TABLE S.II. The same as Table S.I, but for SAMi EDF.

Nuclei	^{17}F-^{17}O	^{15}O-^{15}N	^{41}Sc-^{41}Ca	^{39}Ca-^{39}K
Particle (hole)	$1d_{5/2}$	$(1p_{1/2})^{-1}$	$1f_{7/2}$	$(1d_{3/2})^{-1}$
Finite size	−0.050	−0.068	−0.063	−0.080
Center-of-mass	0.021	0.029	0.014	0.018
$\delta^1_{\rm NN}$	0.014	0.007	0.031	0.021
$\delta^2_{\rm NN}$	0.047	−0.090	0.131	−0.098
Spin-orbit	−0.061	0.078	−0.121	0.140
pn mass difference	0.035	0.026	0.041	0.034
$\delta_{\rm pol}$	0.018	0.073	0.036	0.020
Vacuum polarization	0.019	0.020	0.035	0.037
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bars with error bars and the blue bars, respectively.

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TABLE IV. Contributions from the Skyrme CSB interactions to $\delta_{\rm ONS}$ in Case I and Case II with theoretical uncertainties. The values are given in unit of keV. The core density and the wave function of valence orbit are calculated by HF model with Skyrme EDFs, SGII and SAMi. All the values are obtained self-consistently.

	Nuclei	^{17}F-^{17}O	^{15}O-^{15}N	^{41}Sc-^{41}Ca	^{39}Ca-^{39}K
	Orbital	$1d_{5/2}$	$(1p_{1/2})^{-1}$	$1f_{7/2}$	$(1d_{3/2})^{-1}$
SGII	$\tilde{s}_0$	229^{+192}_{-125}	269^{+221}_{-148}	292^{+245}_{-160}	322^{+264}_{-176}
	$\tilde{s}_1$ ($\tilde{s}_2 = 0$)	$-5.0^{+2.8}_{-4.0}$	$-5.6^{+3.1}_{-4.5}$	$-6.6^{+3.7}_{-5.3}$	$-6.0^{+3.4}_{-4.9}$
	$\tilde{s}_2$ ($\tilde{s}_1 = 0$)	$-6.4^{+3.5}_{-5.2}$	$-3.3^{+1.8}_{-2.7}$	$-5.3^{+2.9}_{-4.3}$	$-5.0^{+2.8}_{-4.1}$
	Case I	224^{+192}_{-125}	264^{+221}_{-148}	287^{+245}_{-160}	315^{+264}_{-176}
	Case II	225^{+192}_{-125}	266^{+221}_{-148}	289^{+245}_{-160}	316^{+264}_{-176}
SAMi	$\tilde{s}_0$	211^{+174}_{-115}	274^{+225}_{-152}	278^{+230}_{-151}	324^{+269}_{-180}
	$\tilde{s}_1$ ($\tilde{s}_2 = 0$)	$-5.2^{+2.9}_{-4.2}$	$-5.4^{+3.0}_{-4.4}$	$-7.3^{+4.0}_{-5.9}$	$-8.4^{+4.6}_{-6.6}$
	$\tilde{s}_2$ ($\tilde{s}_1 = 0$)	$-4.1^{+2.3}_{-3.3}$	$-3.2^{+1.8}_{-2.6}$	$-5.7^{+3.1}_{-4.6}$	$-5.2^{+2.9}_{-4.2}$
	Case I	206^{+174}_{-115}	269^{+225}_{-152}	271^{+230}_{-151}	321^{+269}_{-180}
	Case II	207^{+174}_{-115}	271^{+225}_{-152}	272^{+230}_{-151}	322^{+269}_{-180}

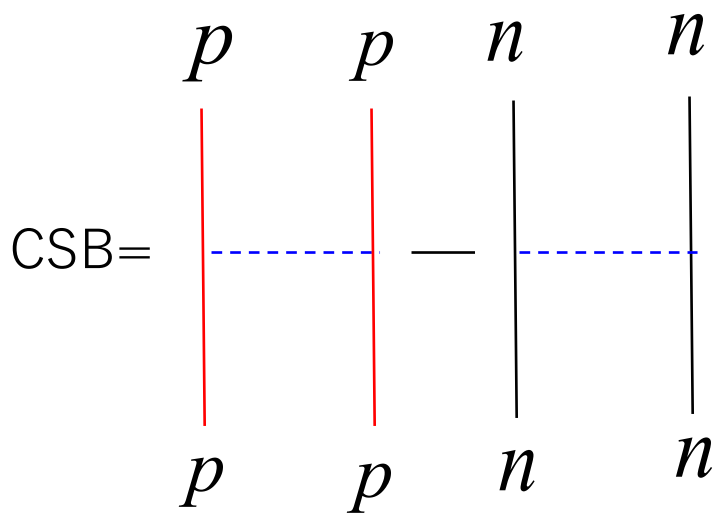
Hatsuda et al. (QCD sum rule; PRL66, 2851 (1991))
290.+/-70. 530.+/-140. 420.+/-110. 570.+/-150.

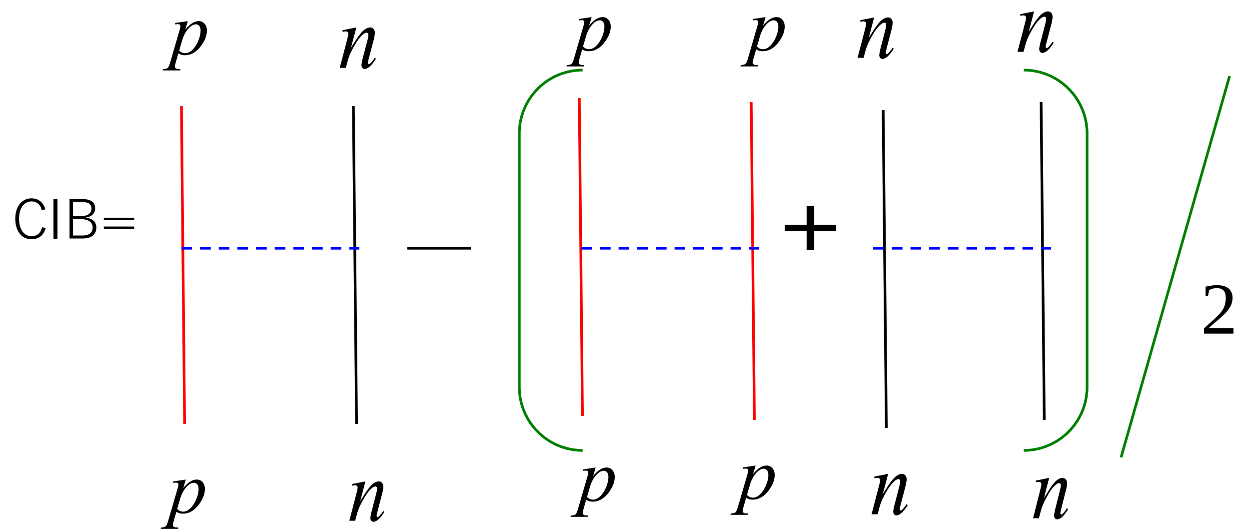
M. Kimura et al.($\rho - \omega$ coupling in RM; PLB367, 5 (1996))
70-290 keV

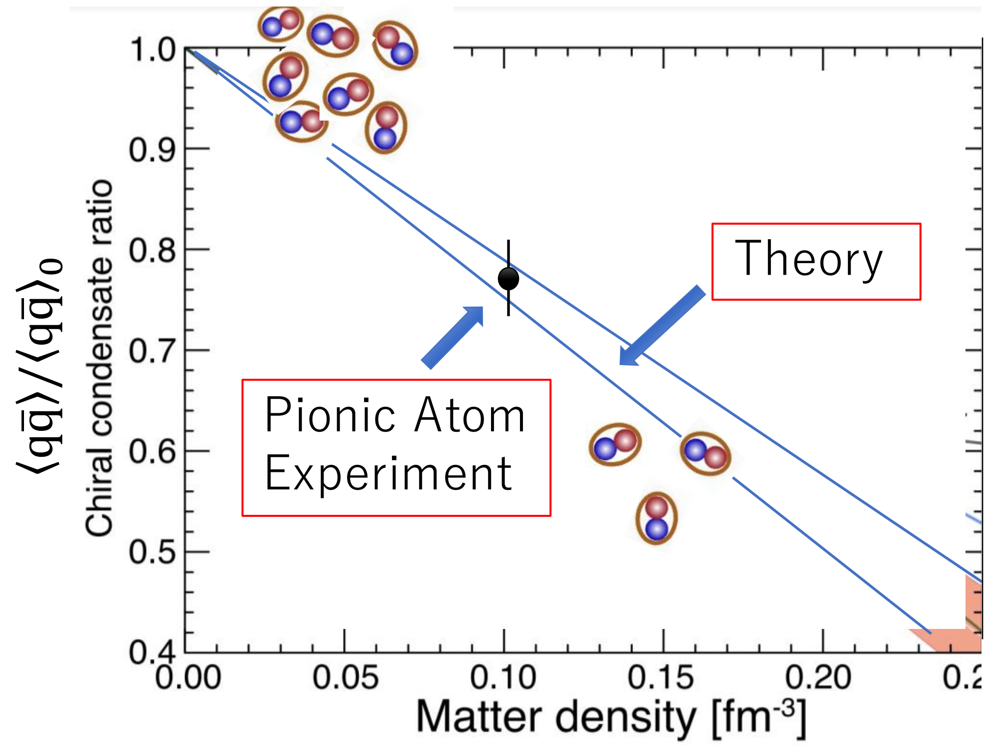
Explicit chiral symmetry breaking

$(p) = (uud) \qquad m_u \neq m_d$

$(n) = (udd) \qquad q_u \neq q_d$







QCD sum rule

Spontaneous symmetry breaking (SSB)

$$m_N = \{ -2(2\pi)^2 < \bar{q} q > \}^{1/3}$$

QCD-based CSB interaction

HS, T. Naito, X. Roca-Maza and T. Hatsuda, PRC109, L011302 (2024)

1. QCD sum rule approach to evaluate mass difference of proton and neutron in nuclear medium
2. Partial restoration of Spontaneous symmetry breaking (SSB) in nuclear medium

The mass difference between neutron and proton is formulated in nuclear matter by the QCD sum rule approach in leading order of the quark mass difference and QED effect

$$\Delta_{np}(\rho) \simeq C_1 G(\rho) - C_2,$$

$$G(\rho) = \left(\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0}\right)^{1/3}.$$

IN VACUUM,

$$\Delta_{np}(0) = m_n - m_p \simeq 1.29 \ \text{MeV}.$$

Here, $\langle \bar{q}q \rangle$ and $\langle \bar{q}q \rangle_0$ are, respectively, the isospin averaged in-medium and in-vacuum chiral condensate. The coefficient C_1 is proportional to the u-d quark mass difference δm [1], through the isospin-breaking constant $\gamma \equiv \langle \bar{d}d \rangle_0 / \langle \bar{u}u \rangle_0 - 1$ as $C_1 = -a\gamma$ with a positive numerical constant a determined by the Borel QSR method

T. Hatsuda, H. Høgaasen, and M. Prakash, QCD sum rules in medium and the Okamoto-Nolen-Schiffer anomaly, Phys. Rev. Lett. 66, 2851 (1991).